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# A SINGLE-PHASE RAILWAY MOTOR.

BY E. F. ALEXANDERSON.

The various single-phase railway motors which have been developed during the past few years have been styled in general as either repulsion or as series motors.

The characteristics of the compensated series motor are well known; they comprise an armature, an exciting winding, and a compensating winding, usually all connected in series. One of the principle objections to this type of motor is the generation of an electromotive force in the coils of the armature which are short-circuited by brushes at the instant of commutation, due to the alternating character of the field. On this account this motor is limited to use on low terminal voltages.

The repulsion motor (invented by Elihu Thomson) has a short-circuited armature and a rotating flux. At speeds near synchronism the electromotive force of alternation in the short-circuited coils is counterbalanced by an electromotive force of rotation. The energy is introduced into the stationary winding and the motor can be wound for any desired voltage.

The most prominent types of single-phase railway motors which have found commercial application are:

1. The compensated repulsion motor (Latour-Winter-Eichberg). This motor has a short-circuited armature and an extra set of brushes for producing compensation, with a view to obtaining a higher power-factor.
2. The compensated series motor (Eickmeyer-Stanley-Lamme).
3. The compensated series motor with shunt-excited commutating poles (Milch-Richter). In this motor, a commutating field is produced locally by coils in the stator.

The motor to be discussed in this paper is neither a series nor a repulsion motor in the generally accepted sense, but embodies the best features of both. For lack of a better name it may be called a "series repulsion motor". The windings resemble those of a series motor, and the armature and stator are permanently connected in series. A general diagram of the motor is shown in Fig. 1. The terminal voltage of the series repulsion motor can be selected with greater liberty than in a series motor, but not so arbitrarily as in the case of a repulsion motor.

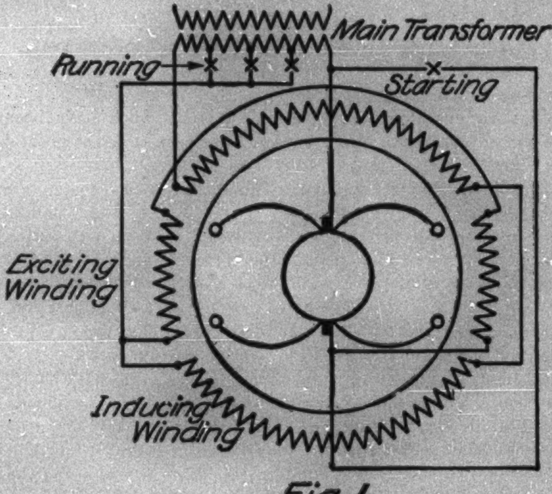

Fig. 1.

Its advantages over the straight compensated series motor are very marked. The commutation is so radically improved that resistance leads are unnecessary and it is feasible to build the motors in larger capacities.

In its performance it resembles the series motors with commutating poles, but offers several distinct advantages over the same. Instead of producing a commutating flux locally by coils on the stator, the conductors in the armature are located in such places where the desired flux will naturally exist. This arrangement simplifies the stator winding considerably. The compensating winding of the series motor is replaced by an inducing winding with twice as many turns, and the energy is introduced either in the stator alone or in the stator and rotor together. By this arrangement, as will be explained later, the starting torque is doubled for the same commutation and the same supply of current.

In the compensated repulsion motor the commutating field becomes too strong as soon as the speed appreciably exceeds synchronism, unless special arrangements are made to suppress this field locally. The motor under consideration is not limited by the synchronous speed, as the repulsion motor feature is reduced at the high speeds, and its action follows more closely the performance of a series motor; the number of poles can therefore be selected with the same liberty as in a series motor. This is of great importance for the motor characteristics, particularly in regard to weight and starting torque. Furthermore, no extra set of brushes, nor any series transformer, is required, which makes the motor equally well adapted for direct and alternating current. These being the most important general characteristics of the motor, there are a number of features which are of interest, particularly to the designer. Before entering into these details it will be necessary to give the general theory of the repulsion motor, together with the general theory of commutation.

The pure repulsion motor has a rotating field, and it appears plausible that commutation may be good in a rotating field, provided the armature rotates at approximately the same speed as the field. However, a rotating field is not in itself a guarantee of good commutation.

When the field becomes ellipitical in shape, it is difficult to grasp the phenomena of commutation unless the field is resolved into its components and expressed as functions of time and space. If this is done, the following field components influence the commutation, as illustrated in Fig. 2.

A. The "main field", which is the torque-producing field, and corresponds to the field in a series motor.

B. The cross-field magnetized by an exciting current flowing in the armature, and serving to transfer the energy from rotor to stator. This field is in quadrature with the main field in time as well as space.

C. Another cross-field magnetized by the difference between the ampere-turns of the armature and the inducing winding. This field is in phase with the main field.

D. The leakage flux around the commutated coils.

The conditions for perfect commutation are as follows:

1. The electromotive force of alternation of the main field should be neutralized by the electromotive force of rotation in the cross-field designated " B ".

2. The magnetomotive force of the stator should be larger than the armature reaction; the difference, which is the field designated " C ", should be large enough to overcome the voltage due to the leakage flux.

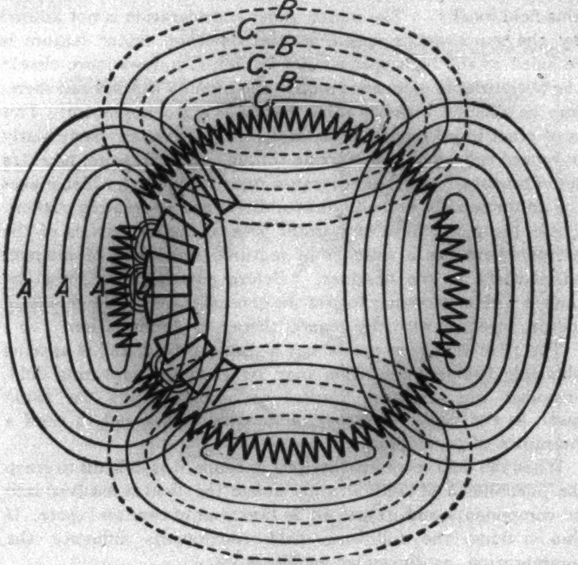

Fig. 2

If these conditions are fulfilled, the commutation is identical with that of a direct-current motor with commutating poles.

The first condition is found at synchronous speed in a repulsion motor, and theoretically in a series motor at infinite speed.

In a series repulsion motor it can be obtained at any speed by varying the proportion between series and repulsion motor action.*

This, however, meets only one of the fundamental conditions necessary for good commutation; there are others which will affect commutation as much as will shifting the brushes of a direct-current motor from the right to the wrong side of the neutral.

The type of motor which is generally referred to as a repulsion motor is that with a continuous stator and rotor winding, and the brushes shifted in the direction of rotation as in Fig. 3.

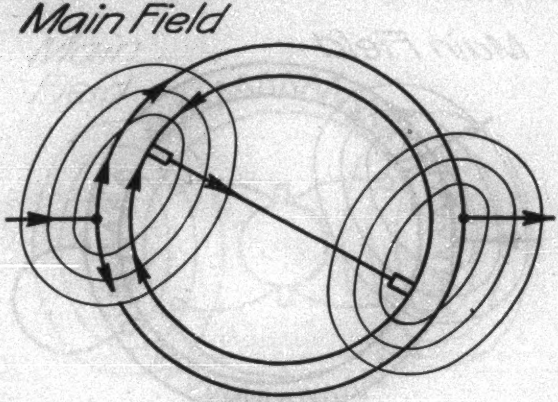

Fig. 3

If such a motor is used as a series motor with the stator and rotor connected in series, it is apparent from the diagram shown in Fig. 4 that that part of the windings which is included in the angle represented by the shift of the brushes constitutes the exciting coils, and the lines of force are distributed as shown on the diagram. The brushes are shifted in the direction of rotation and are located on the edge of the active field. It is well known in direct-current practice that the brushes of a motor ought to have a backward shift, if any, but never a forward shift; and it is therefore obvious, considering the direct-current features that this motor cannot commutate well. In the repulsion motor, the armature currents are induced by the transformer action, but the distribution of the currents is substantially the same as described above for the series motor. This difficulty has led to the design of an armature winding as shown on Fig. 5, by which the electromotive force due to the cutting of the active flux is eliminated. The magnetization is produced by a separate stator winding located symmetrically with respect to the brushes. This gives a distribution of the fields as shown in Fig. 5. The armature conductors under commutation are located on the edge of the field flux, so that both sides of the coil are under an equal flux of the same polarity.

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* Diagrams have been shown by Milch & Latour with a voltage impressed on the armature circuit in order to meet this condition.

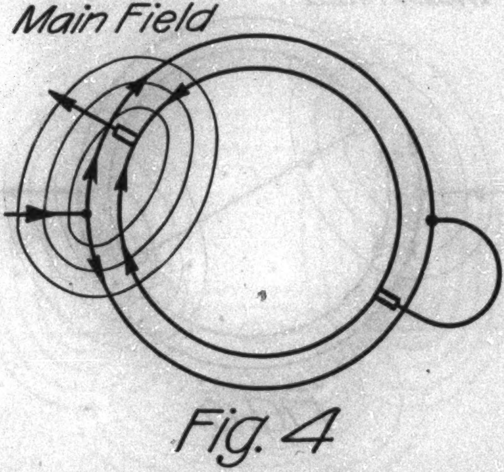


Fig. 4

There is another way of looking at this phenomenon which leads to the same result: the winding of the repulsion motor can be separated into an exciting winding and an inducing winding, in this case the brushes are located in the neutral of the stator winding. The armature is the short-circuited secondary of the inducing winding and must consequently have substantially the same total number of ampere-turns. The two fields that are excited by the stator and rotor individually are shown in Fig. 6 (*a*). The rotor field is peaked and stator field is flat-topped, giving a resulting field as shown by the cross-section part of the diagram. Consequently, there is a resulting peaked field opposite to the brushes where the conductors under commutation are located. This field is excited by the armature and has all the detrimental effects of armature reaction. Fig. 6 (*b*) shows how this is overcome by a fractional pitch winding on the armature. It also shows why only one definite winding pitch gives the correct result, whereas a greater or less ratio gives a field in the wrong direction.

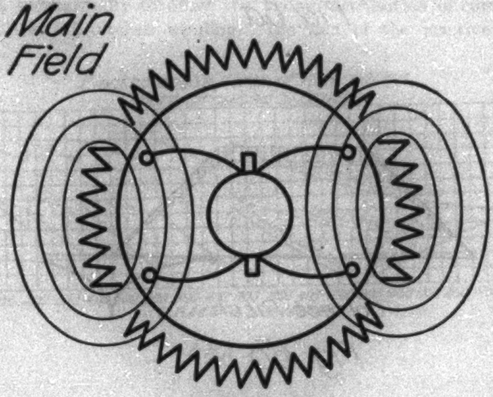
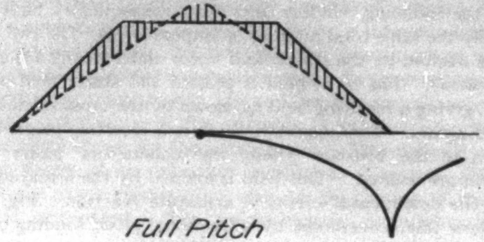


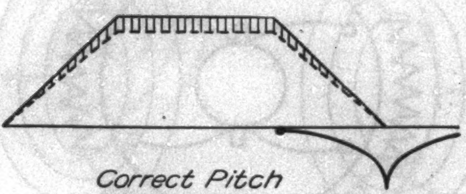
Fig. 5

The correct combination in Fig. 6 (*b*) shows the rotor flux slightly lower than the stator flux, whereas if there were no leakage the currents and corresponding fluxes would be equal, but actually, the primary is a little higher due to the leakage. The difference between these two fluxes acts as a commutating field; but, on the other hand, the higher the leakage, the higher will be the commutating flux needed to overcome the leakage.



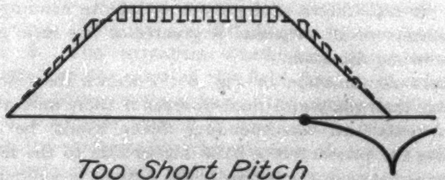
Full Pitch

Fig. 6a



Correct Pitch

Fig. 6b



Too Short Pitch

Fig. 6c

If, however, the armature is short-circuited through a reactive coil, the resulting flux is increased without introducing leakage in the armature. Since the field of the motor is a reactive coil itself that must be excited, a convenient way of introducing reactance into the motor armature is to use the motor field or a part thereof for this purpose. That it is beneficial for the commutation of a repulsion motor to introduce the field in the armature instead of the stator circuit was experimentally demonstrated long ago by E. W. Rice, Jr. The reason for the improvement as explained above, is that the reactance of the field changes the ratio between stator and rotor ampere-turns so as substantially to offset the wrong distribution of currents with the full-pitched winding. The fact of the reactive coil being the field winding is in this respect immaterial, and it has been proved that the field of a similar machine introduced in the same place gives the same result.

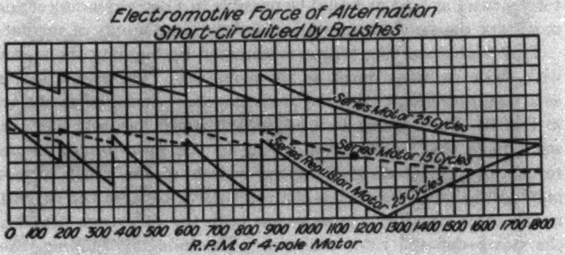


Fig. 7

The above discussion demonstrates how the two fundamental conditions for good commutation can be fulfilled in a series repulsion motor at any speed without the aid of commutating poles. Instead of creating a commutating flux artificially in a place where the commutated conductors happen to be, the conductors are located in a place where the correct flux will naturally exist. By controlling the value as well as the phase of the different fluxes as described, perfect commutation can be obtained at any speed.

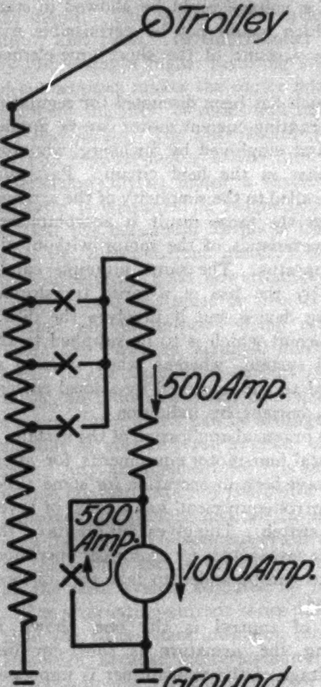
Fig. 7 gives a comparative diagram of the alternating voltages in the short-circuited coils of a series repulsion motor for 25 cycles and for the same motor when used as a series motor for 15 and 25 cycles. The improvement introduced by the fractional-pitch armature winding is a separate matter and is of the same character as the change from an ordinary direct-current machine to a commutating-pole machine.

## STARTING

The starting of a single-phase motor is materially handicapped by the fact that the alternating nature of the main field sets up currents in the armature coils which are short-circuited by the brushes. This same difficulty is experienced in all known types of single-phase commutator motors. Although the principle involved is the same in the motor under consideration, the practical result gained by the arrangement employed is a starting torque twice as high as would be possible in a corresponding series motor for the same commutation and the same supply of current.

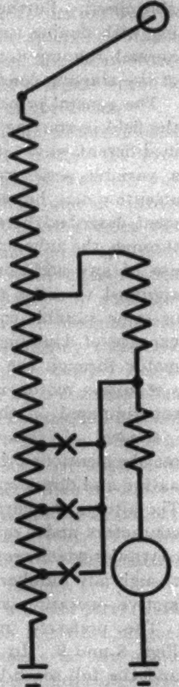
This double starting torque is obtained by winding the stator with twice as many turns as the armature. The motor starts as a repulsion motor with the armature short-circuited as shown in Fig. 8. The current as it enters the stator has only half the strength of that in the rotor, owing to the ratio of stator to rotor turns. The short-circuiting switch of the rotor carries only half as much current as the rotor itself, because the current in the short-circuited connection is only the difference between the stator and the rotor current. The inducing winding, the field, and the armature are connected permanently in series; but with the connections shown, the field is in series with the stator circuit at starting and with the rotor circuit when running. In starting, the rotor carries twice as much current as when running, in order to give the same field strength—in this manner doubling the starting torque. The sparking at starting is quite insignificant up to a certain value of the voltage short-circuited by a brush, but beyond this point the commutation rapidly becomes bad. This critical value is about the same as that which gives a reasonably good commutation in running. For a pure compensated series motor, therefore, the same remedy must be looked for in running as in starting conditions, and the natural solution is to design the motor for a low voltage or to use resistance leads.

In ordinary series motor equipments, the difficulty arises that a higher starting torque is usually required than the full-load running torque, and if the short-circuited voltage is permissible in running, it will get too high at starting. A starting torque of twice full load (one-hour rating) torque is, however, usually more than enough, and therefore the short-circuited voltages can



Starting

Fig. 8



Running

Fig. 9

be kept below the critical point, while the torque is increased above normal. It is, however, not only the critical value of the voltage, but also the time that such a voltage is maintained that determines what is permissible. In this respect any repulsion motor has a great advantage, because the sparking disappears altogether as soon as the armature has reached an appreciable speed. Furthermore, a voltage could be allowed in starting with double torque which would not be permissible with normal running torque, on account of the short time-element of the starting condition.

The general principle which has been discussed for regulating the field in starting an alternating-current motor can be applied in different ways; it was first employed by Eichberg, who used a variable series transformer in the field circuit. Particular attention may, however, be called to the simplicity of the arrangement described here, where the same result is acccomplished through the inherent characteristics of the motor without the use of any additional apparatus. The same principle can be appplied to series motors by the use of a series transformer or some suitable controlling device, but it involves the disadvantage of doubling the current which is to be supplied to the motor through the control system, whereas when starting as a repulsion motor, increased torque is gained by a local current superimposed on the main current by induction.

*Control.* In regard to the practical application of the system, it may be mentioned that several four-motor equipments for alternating and direct current have been in operation for some time. The alternating-current control equipment has a total of seven contactors and a reversing switch. This gives four points on the controller which seems quite satisfactory for motor-car operation, though any number of steps can be added to take care of locomotive operating conditions.

The preferred method of control is the one shown in Figs. 8 and 9. In starting, the armature is short-circuited and the full secondary voltage of the transformer is impressed upon the inducing and exciting windings. The current flowing through the stator continues through the armature, but due to the ratio of turns of inducing winding and armature winding, an additional current of equal strength to the stator current flows through the local circuit of the armature and the short-circuited connection. In the running connection, part of the power is introduced in the stator and part in the rotor, and the field winding carries the same current as the armature; that is, twice the stator current, thus giving a relatively greater field strength than in the starting condition, just as would be produced by a series-multiple connection of the field winding.

Although the total potential impressed upon the stator and rotor is the same for starting and running, the result of changing the connection so as to transfer the energy input from the stator to the rotor has the effect of increasing the resulting voltage of the motor. This is due to the ratio of transformation between stator and rotor. In this manner a higher speed is obtained by impressing a higher resulting voltage, and the same change of connections makes the motor adapted for a higher speed by changing the ratio of series and repulsion motor action.

*Power-factor.* The only motor that has an inherent claim on unity power-factor is the direct-current motor. In every alternating-current motor a certain amount of wattless volt-amperes is consumed in magnetizing the field, and in leakage, so that the maximum torque is limited to a lower value than with the direct-current motor. An alternating-current motor with inherently good power-factor is one with high overload capacity, and this must be due to a comparatively small proportion of volt-amperes being consumed for magnetization. There are, however, artificial methods of bringing the power-factor of the alternating-current motor up to unity. For example, an induction motor can be shunted by a condenser, and a commutator motor can be arranged so as to generate a certain amount of volt-amperes in order to supply its own magnetization. Any arrangement for this purpose does not improve the torque characteristics of the motor, any more than a condenser improves the performance of the induction motor; it improves only the phase displacement of the supplied current. The effect on the system can be corrected equally well by other machines on the same system adjusted for leading current.

The alternating-current series motor has a higher power-factor than the three-phase induction motor with the same magnetic structure, because the series motor generates a certain amount of volt-amperes. The power-factor of a series alternating-current motor can be increased to unity by displacing the phase of the field current; for instance, by shunting the field with a non-inductive resistance. In fact, the higher power-factor is due to internal shunt currents, the core-loss as well as the short-circuit current in the brushes having the character of shunts on the field winding. Eliminating the core-loss as well as the short-circuit currents in the brushes would, therefore, evidently improve the motor itself, although it would lower the power-factor.

The following is a short statement of the functions of the different fluxes in a repulsion motor. The motor is understood to be designed, as described before, with a definite degree of fractional pitch and the brushes in the neutral position.

*Power-factor of the repulsion motor with field winding in stator circuit.* In a repulsion motor, the current passing through the inducing winding produces a corresponding current in the armature. By the rotation of the armature in the main field, an electromotive force is generated in the armature, which causes a magnetizing current which is superimposed upon the main current, and it is this magnetizing current that causes the voltage to be transformed back to the primary. In other words, the current is transformed from the stator to the rotor and the electromotive force generated in the rotor is transformed back to the stator. One flux is needed to transform current and another flux to transform the voltage. These two fluxes are out of phase. The voltage flux is generated in the armature by rotation and does not consume any volt-amperes from the line. The main flux as well as the current flux and the leakage flux consume volt-amperes.

*Power-factor of the repulsion motor with field winding in armature circuit.* The theory of this motor is the same as above, except that it takes more flux to transform the current because the armature circuit includes the impedance of the field. Why this increased flux is good for the commutation has been shown above. The same magnetizing current for the voltage flux as described above flows through the armature, and in this case through the field also. This magnetizing current displaces the phase of the main field, and consequently the electromotive force of the machine. The displacement tends to lower the power-factor and the result is the same as if the volt-amperes of the voltage flux had been supplied from the line. In other words, the motor has the same inherent power-factor as a single-phase induction motor.

A series repulsion motor as developed for railway service has only one-third to one-quarter repulsion motor action, this being the proportion that gives sparkless commutation from synchronous to double synchronous speed. The lowering of the power-factor due to magnetizing current is therefore very slight, and with the greater liberty in design that is gained in the series repulsion motor, the power-factor is practically the same as in a series motor.

The analysis of the phase displacement also indicates how the power-factor can be corrected by shifting back the phase of the field current. This can be done in the series repulsion motor as well as in the series motor by shunting the field by a resistance according to the suggestion of Mr. A. S. McAllister. It can also be done, as has been experimentally demonstrated, by a slight degree of separate excitation of the field derived from the main transformer or from the stator coils. However, any raising or lowering of the power-factor of phase displacement does not affect the tractive effort or heating of the motor; it only changes the voltage that has to be applied in order to overcome the inductive drop. As soon as any artificial method of raising the power-factor involves any complication, for instance, another set of brushes on the commutator, it will probably prove preferable to improve the constants of the system by using synchronous machines wherever power is used for other purposes.

*Resistance leads.* The use of resistance leads, which has been so much discussed, has been found to be unnecessary in motors of the type described. Certain motors which have been operated for a considerable time as series motors, and then rewound so as to embody the features described in this paper, have shown an increased life of brushes and commutator up to the standard of good direct-current practice. The improvement in commutation was so great that it was possible at the same time to increase the thickness of the brush and the output of the motor.

*Selection of frequency.* In regard to choice of frequency, the series repulsion motor again gives greater liberty. Whereas the starting torque can be doubled on either 15 or 25 cycles, it may be mentioned that a series motor which was almost inoperative at a certain load at 25 cycles, after rewinding, as described, was tested as a series repulsion motor, and found to give excellent commutation at 40 cycles, at the same load. It can therefore be said in general that 25 cycles is entirely satisfactory for all geared motor work; it is preferable in that the combination of motor and transformer weighs less at 25 than at 15 cycles.

A general discussion of the selection of frequency really falls outside the scope of this paper, as the motor referred to is equally well applicable to 15 or 25 cycles. It is, however, the impression of the author that the only argument that remains for 15 cycles is the direct-connected motor for high-speed passenger locomotives. It is, therefore, a question whether the policy of the railroads in regard to frequency should favor 15 cycles because of the requirements of the design of a particular type of locomotive with a limited use, when the freight work as well as the multiple-unit motor trains can be handled more economically at 25 cycles.

*Economy of material.* The motor described can be built in larger capacities than the series motor. The principal reason for this is the inherently good commutation and increased starting torque which make resistance leads unnecessary, thereby eliminating the heat generated by the resistance leads, and also gaining space in the slots, which can be used for copper. Furthermore, it is possible to increase the flux per pole without impairing the commutation.

The fractional pitch winding which is used primarily for the sake of commutation is also advantageous from the point of view of economy of material. The saving extends not only to the end-connections, as is the case with the fractional-pitch induction motors, but also to the stator winding, inasmuch as only the active armature conductors, or only about 80% of the total, need to be compensated for; whereas with the full-pitch armature, the entire winding must be compensated for. In neither case is it possible to utilize more than about 80% of the total pitch as effective pole arc, because of the space occupied by the field winding. This principle is applicable to any type of compensated machine of the Deri type for alternating or direct current, except when the commutating pole is used.

The fact that the number of poles in the series-repulsion motor can be selected without regard to the synchronous speed is an important consideration. The tractive effort of an alternating-current motor referred to the periphery of the armature is directly proportional to the number of poles employed, provided that the same flux per pole is used and the same current density in amperes per inch of circumference. The allowable flux per pole depends upon the type of winding and thickness of brush, but the same limitations exist for all known types of motors. The formula for tractive effort given below is deduced from the fundamental formulas for commutator machines, but it is of special interest because it brings all motors to the same basis and shows the advantage of liberty in selecting the number of poles.

The tractive effort in kilograms at armature periphery =

$$\text{amperes per cm.} \times \frac{\text{flux}}{\sqrt{2}} \times \text{number of poles} \times \frac{1}{9.8}$$

The only constant in this formula is the acceleration of gravity, 9.8, in the metric system.

Tractive effort in pounds at armature periphery =

$$\text{amperes per inch} \times \frac{\text{flux}}{\sqrt{2}} \times \text{poles} \times 0.089$$

This formula also indicates which method can be considered to obtain as high a starting torque as possible with a given number of poles. The starting torque depends only upon the flux per pole and the current-density. The permissible flux can be slightly increased by use of resistance leads. A considerably larger increase can, however, be obtained by raising the current density momentarily without changing the flux. This is the method that has been adopted in the motor described.

At first glance it may appear that this method would lead to an overheating of the winding. This, however, is not the case. In a motor of this type the $I^2R$ losses are of about the same magnitude as the losses due to the field and the rotation. The total losses of the motor are therefore not increased by the square of the current, but more nearly in proportion to the current. Furthermore, when an increased starting torque and increased acceleration are obtained by increased current, the duration of the excessive current will be so much shorter, with the result that a train can be brought up to a certain speed with only slightly higher heating if this is done at a higher rate of acceleration and with the use of an increased current.

In summing up the preceding the particular advantage of the motor described may be claimed to be:

1. Good commutation at all speeds without the use of resistance leads.
2. Larger capacities possible than with the series motor.
3. High tractive effort possible, due to the liberty of selecting the number of poles.
4. Increased starting torque, possible because of the inherent ratio of winding turns, without supplying an increased current from the main transformer.
5. Simplicity of construction. The stator is the same as in the series motor, in fact easier to construct due to the greater liberty of placing the field-winding in slots. The armature is constructed according to standard direct-current practice with the conductors soldered into the commutator bars.
6. Equally well applicable to direct and alternating current.

## DISCUSSION ON "A SINGLE-PHASE RAILWAY MOTOR." NEW YORK, JANUARY 10, 1908.

**L. B. Stillwell:** The announcement of a new motor is always interesting. When its novel features are such as tend to material improvement of performance or reduction of cost, it is not only interesting but important. When to improvement of performance and reduction of cost is added the consideration that the new motor is of a type upon the success of which depends largely the solution of the most weighty problems that electrical engineers are called upon to solve, the publication of the results of the inventor's work is an event in the annals of engineering.

Mr. Alexanderson and his associates are to be congratulated upon the production of a single-phase alternating-current motor possessing apparently at least one feature of marked originality and of much practical value—the elimination of the idle resistance in the armature winding is an important step. I have not been able to ascertain from the paper how much this step costs in other directions. The author states frankly that the motor is a compromise, combining, as he believes, the good features of the series compensated motor with those of the repulsion motor. Whether the compromise is an advantageous one, whether the characteristics of the new motor, under the conditions imposed in practical service, are such as render it, on the whole, superior to its competitors, is the question at issue.

The question of superiority is to be determined by comparison, not of one but of a number of factors. The strong point of the new motor appears to be its ability to commutate at high speed without sparking; at the moment of starting, however, the sparking apparently may be serious. Further light should be thrown upon this point. It would be interesting also to know what the power-factor is, both at starting and at speed.

But more important than either of these is the ratio of output to weight, since in heavy railway traffic motors must be placed within certain defined limits of space; for other things being equal, the best motor is the one that, within such limits and within reasonable limits of temperature and commutation, is able to deliver the largest sustained output.

In the paper entitled, "On the Substitution of the Electric Motor for the Steam Locomotive", presented at the 214th meeting of the Institute by Mr. H. S. Putnam and myself, the question whether 25 cycles or a lower frequency; for example, 15 cycles, should be adopted for heavy railway work was asked, and the opinion was expressed that "a frequency of 15 cycles is preferable and should be adopted." The oral discussion was energetic, and in the written discussion with which it was closed Mr. Putnam and I incorporated the following statement of opinion and summary of the positions taken by a number of distinguished engineers who had participated in the discussion:

> The oral discussion which followed the presentation of the paper was conclusive, beyond our expectation, as regards frequency. So far as the

general practice of engineers who may adopt the single-phase alternating current is concerned, we regard the matter as practically settled by the facts and opinions brought out by the discussion. The designing engineers of both the Westinghouse and General Electric Companies testified emphatically to the great increase in power of motors which can be realized by reducing the frequency, and while several speakers questioned the wisdom of now adopting a standard, no one came forward to argue that the higher frequency is preferable.

Mr. Lamme, to whom, more than to any other man, we owe the single-phase motor, stated that at 15 cycles the output of a given motor is from 25% to 40% greater than at 25 cycles and that his company had verified this by actual test.

Mr Storer testified that: 'You can get at least 30% greater output from motors with 15 cycles than with 25 cycles'.

Mr. Slichter, the engineer of the General Electric Company, who has immediate charge of the work of designing single-phase motors, said: 'There seems to be a unanimous opinion that the output of the motor may be increased some 30% to 35% by a decrease in frequency from 25 to 15 cycles.'

Mr. Potter, chief engineer of the Railway Department of the General Electric Company, after pointing out some of the difficulties in the way of the adoption of 15 cycles, said: 'I do not think, however, that we can look for the ultimate development of the single-phase motor of 25 cycles'.

* * * *

The paper and the discussion have established the fact that the increase in cost of the power house equipment consequent upon the suggested reduction in frequency is far more than offset by the reduction in cost of electric equipment of rolling stock consequent upon the adoption of 15 cycles.

During the discussion of Mr. Sprague's paper presented on May 21, 1907, announcement was made of a new motor which it was claimed performed so well at 25 cycles that the argument in favor of 15 cycles for heavy railway work was materially weakened. The motor referred to was that which has been disclosed this evening by its inventor.

In Mr. Alexanderson's paper little is stated relatively to performance of the new motor at frequencies lower than 25 cycles per second beyond the statement in reference to its commutation that it, " is equally well applicable to 15 or 25 cycles ", and that " it can, therefore, be stated in general that 25 cycles is entirely satisfactory for all geared motor work; it is preferable in that the combination of motor and transformer weighs less at 25 than at 15 cycles." Regarding the statement that the commutation is equally good at 25 or 15 cycles, it is to be regretted that the author does not show in Fig. 7 the curve of the electromotive force of alternation short-circuited by brushes when the motor is operated at 15 cycles. It is obvious that commutation at 15 cycles will be improved, and there is no reason suggested why this improvement, expressed in percentage, should not be as great in the case of this motor as in that of the series compensated motor. In the second statement quoted, one of the principal advantages of the lower frequency is entirely ignored. The relative aggregate weight of motor and transformer is unquestionably important, particularly in multiple unit work; but much more important, at least in the field of heavy electric traction, is the power of the motor that can be placed in a given space on the truck. The factor of cost is also against the 25-cycle motor. From the facts given, I believe that this new motor will gain as much in ratio of output to weight at a given speed by reduction of frequency from 25 to 15 cycles, as will the series compensated motor.

It seems to be a fair generalization to say that alternating-current motors having speed characteristics resembling those of the direct-current series motor will gain approximately 30% in torque, and will also gain materially in sustained power by reducing the frequency from 25 to 15 cycles per second. I find nothing in Mr. Alexanderson's paper to indicate that this motor is an exception to the general rule. If I have not understood it I shall be most happy to be corrected, as no one can question the weight of the arguments against the adoption of a new standard frequency, and such adoption can be justified only by the existence of controlling considerations such as those to which I have referred.

**B. G. Lamme:** This paper describes a certain type of single-phase commutating motor, and comparison is made with the series compensated type, generally to the apparent disadvantage of the latter. It is intimated that this motor does what the series compensated motor cannot do. The theme of the paper appears to be that successful commutation of alternating currents has at last been obtained. Instead of accepting these conclusions, I am free to state that I do not see that this motor does, or can accomplish more than has already been accomplished successfully by a properly designed series compensating motor. Further, I claim that the series compensated type, as already built, is in certain features so far ahead of the type described in this paper, that it looks like exaggeration when a comparison is made in figures. In this paper, describing what is claimed to be a new and superior type of motor, no characteristic curves or data are given, and consequently no quantitative comparison can be made with other designs.

Let us first consider the starting conditions and characteristics. The general scheme of starting is based on the use of a relatively weak field at the beginning, the field induction being increased, for the same torque, after sufficient speed has been attained to make the commutating poles effective. Theoretically, assuming no saturation of the magnetic circuit, this increase in induction could be approximately 41 per cent, but practically it would be but 20 to 30 per cent., the material in the machine being worked economically. The object of this relatively weaker field at start is to lower the voltage in the coils short-circuited by the brushes. Referring to commutating motors in general, the author says:

> The sparking at start is quite insignificant, up to a certain value of the voltage short-circuited by the brush, but beyond this point the commutation rapidly becomes worse.

The author admits that it is necessary either to keep below this critical voltage or to use preventive leads. This is the parting of the ways. It is either necessary to limit the design of the motor to such proportions that the induction at start can be kept down to such a low value that the short-circuit voltage is below the critical point, or, to take a broader course, to use preventive devices and thus raise the critical point and increase the output and improve the performance. Apparently the author does not believe that preventive leads, or resistance leads as he calls them, permit sufficient increase in the short-circuit voltage to represent any great gain in the operation. I disagree with him here, and will give some figures which I think will bear out my point of view. I am going to compare this arrangement with the series compensated type by assuming both to be applied to a motor corresponding to the present New Haven locomotive motors, which have a normal rating of 250 h.p. at 220 rev. per min. at 25 cycles.

This size of motor is selected for comparison principally because I have more data of various combinations of windings of armature and field than on any other large motor. In bringing through the first New Haven motors numerous arrangements were tested, such as fields with under- and over-compensation, commutating poles, etc., and armatures wound with and also without preventive leads. The combination giving the best all-round results is that used on the New Haven equipments.

These New Haven motors are worked at the time of starting at a high induction per pole, and in consequence at a high short-circuit voltage. Therefore, as this is a practical case it is fair to use it in making the comparison. But before making the direct comparison I shall digress slightly to take up the subject of currents flowing in the armature windings of single-phase commutator motors. Two currents should be considered: first, the working current which is fed into the brush and which passes into the commutator bars, through the connections, or leads, into the main armature winding; and secondly, a local or short-circuit current which passes from the short-circuited coil out through the lead or connection to one commutator bar, then through the brush to the adjacent bar and back through the lead to the coil. This local current is dependent upon the voltage generated in the short-circuited coil and upon the impedance in the closed circuit. If this local current could be limited to values approximately the same as the working current in the coils, then it could be taken care of very readily by the ordinary resistance of the brush, brush contact, etc.; but unfortunately a short-circuit voltage low enough to give this condition would give absurd proportions in the motor. In order to obtain a reasonable capacity from these single-phase motors, it is necessary to work at an induction giving a short-circuit voltage so high that this local current would usually be many times greater than the normal working current in the coils. It is for the purpose of reducing this short-circuit current to a more moderate value that preventive leads are added. It has been assumed that the addition of these leads means an increase in loss. However, as the purpose of the leads is actually to reduce the excessive local current, the result is a very considerable decrease in loss by the use of these leads. The following figures will indicate wherein these leads are beneficial.

Taking up again the comparison which I proposed to make, let us consider that, with either scheme of winding, the motor starts under double normal full load or one-hour torque. This condition occurs very frequently in the operation of the New Haven equipments, and is even very considerably exceeded at times. Under this condition of double torque, the motor with the series compensated winding has an induction of approximately 1.25 times normal and a working current in the armature and field of approximately 1.6 times normal or one-hour current. The preventive leads are so proportioned that the local or short-circuit current at this overload torque is, roughly, about 1.25 times the normal working current in the armature conductors. Next, applying the scheme described in Mr. Alexanderson's paper in order to get twice full-load torque, the field would have normal full-load induction, and the armature would have double normal current, compared with a field of 1.25 and an armature current of 1.6 in the compensated series motor with preventive leads. This double current in the armature with normal field strength would not look so bad if it were possible actually to operate satisfactorily under this condition without preventive leads. But with the high normal induction per pole on the New Haven motors, the tests show that it is utterly impracticable to start with normal induction in the field without preventive leads in the armature, for the short-circuit or local current is excessive and causes vicious and destructive sparking. Our data indicate that, without preventive leads, and using brushes of medium low resistance, such as are used in ordinary generators and motors, this New Haven motor will give a short-circuit of about seven times normal working current in the coils with normal full-load induction in the field. This condition is prohibitive and is far beyond the critical point mentioned before. Even reducing this induction to 70 per cent. of its normal value, the short-circuit current is still about five times normal current, which I consider to be too high. However, let us assume this value. The field strength at double torque would, therefore, become 0.7 instead of normal, and the armature current for the double torque would have to be increased to 2.86 times normal instead of double. The current with this arrangement would then be as follows:

Short-circuit approximately 5 times normal.
Working current 2.86 times normal.

These should be compared with the compensated series arrangement in which these values are:

Short-circuit 1.25 times normal.
Working current 1.6 times normal.

The total current required by the brushes and commutator in the compensated series motor would therefore be approximately one-third that required if the scheme described in this paper were used. Let us carry this analysis a little further. Assuming that we could start satisfactorily with the 0.7 normal induction indicated above, then when speed is attained a 40 per cent. stronger field could only be obtained provided there were no saturation in the magnetic circuit. But taking saturation into account, the increased induction would hardly be 30%. It is evident, therefore, that in order to accommodate the starting conditions, the normal induction must be sacrificed somewhat; and with the highest permissible field at start the normal induction would be considerably lower than if preventive leads were used. Another interesting point to be noted in these figures is the comparison of relative inductions at start with the two arrangements. It may be seen that the motor with preventive leads shows 1.25 times normal induction, while the method proposed in this paper shows 0.7 normal. The gain in induction by the use of preventive leads in this case is approximately 75%, and even with this increase in induction I am confident that this motor would make the better showing as regards sparking and burning at the commutator and brushes during starting, due to the greatly reduced local currents. The above figures also indicate clearly the disadvantage of trying to improve this condition by the use of high-resistance brushes. Necessarily the life of such brushes would as indicated be considerably shortened by the excessive currents.

This method of considering the currents flowing in the armature shows very clearly why 15 cycles is more advantageous than 25 cycles in the alternating-current commutating motor. As the short-circuit voltage is a direct function of the frequency, as well as of the induction, it is evident that with the same limiting short-circuit voltage, the induction could be increased in the ratio of 25 to 15, or 66%. It is evident, therefore, that the limit of induction at start is thus raised enormously. In practice, however, unless the motor is worked at extremely low saturation, the full gain of 66% can not be obtained either at start or at speed; for in order to obtain the greatest economy in weight and dimensions it would be natural to work the material at as high saturation as permissible, and in practice there would be only about 30% gain. As we could work 66% higher with the same short-circuit voltage, this increase of only 30% means that the short-circuit voltage is thus less than 80% that of the 25-cycle motor of corresponding design. There is thus about 30% greater output due to the higher induction, and at the same time this is obtained with a lower short-circuit voltage and therefore with more favorable starting conditions.

I have expanded on this starting condition, for experience with large motors shows that it is a most difficult one to meet in locomotive work. Also, tests indicate that the local or short-circuit current is a maximum at start, being close to the theoretical value, but falls off rapidly as the machine speeds up.

Mr. Alexanderson intimates that even if the losses are excessive in the armature winding at start, yet the quick starting and acceleration will greatly reduce the danger from this source. This may be true of small equipments where light torques are required, and quick acceleration always possible; for heavy work, however, there are many occasions where it is necessary to start very slowly and run slowly for a considerable time. I shall cite some of the tests made with the locomotive equipped with two 500-h.p. motors and exhibited at Atlantic City at the Street Railway Convention last October. This machine was given some very severe tests last summer at East Pittsburg, in the presence of prominent railroad engineers. In some of these tests the locomotive was operated for five minutes at speeds of from two to three miles per hour, and this while exerting more than double torque. This represents less than one-tenth the normal or rated speed of the motor. The motor was also held at standstill for considerable periods, developing excessive torques in attempting to start trains with the brakes set. Under this condition a motor without preventive leads would, unquestionably, have been ruined. This condition of the motors at standstill, with a heavy current flowing, is particularly liable to be met with in freight service, especially if two or more locomotives are working independently with a very heavy train. It will be impracticable to start all the locomotives at the same instant, as they may be in different parts of the train; consequently, one locomotive may develop a high tractive effort at standstill for some little time before the other locomotives are thrown in. To meet such conditions in practice requires a motor that can be held at standstill for more than an instant when developing heavy torque. It has been claimed by some engineers that under this condition the preventive leads, or resistance leads as they are called, must necessarily burn out, because they have a large loss in them at this time. It is under this very condition that the motor with the preventive leads shows to great advantage over the one with excessive short-circuit currents, and without such leads. As mentioned above, this explains why the latter type of motor is liable to be injured during a failure to start; it will not do simply to say that on account of rapid start and quick acceleration the motor will not be injured. In freight service, the opposite condition of starting must be handled with certainty.

It may be said that Mr. Alexanderson's motor is a true commutating-pole type of machine, but instead of using a separate pole placed in the interpolar gap the two edges of the main pole are used as an interpole. This may be illustrated by the following diagrams.

In Fig. 1 is shown the ordinary arrangement of winding with an interpole, the winding being the full pitch. In Fig. 2 the interpole is shown at one side. In Fig. 3 the pitch of the coils is shortened and the interpole is widened a corresponding amount so that this pole still covers the armature coils. The pitch is narrowed until the two sides of the coil lie under the two edges of the main pole. The width of the interpole is, therefore. such that it would overlap the main poles, if superimposed. It is evident that the centre of this interpole is useless and could be cut away as shown in Fig. 4. As this pole overlaps the main poles in position, it is evident that the edges of the main poles themselves could be used as interpoles if the winding surrounding the interpoles is properly placed in the main poles so as to surround these two edges. This is just what the compensating winding does. The effect, therefore, is the same as if interpoles were used, for part of the main pole is converted into an interpole, as shown in Fig. 5. However, since it is evident that part of the main pole is converted into an interpole, it is also evident that part of the main pole, used as an interpole, represents that much loss in the effectiveness of the main pole. In other words, the armature coil does not surround all the induction from the main poles, but only part of it, and in consequence of this reduced effective induction the counter electromotive force of the machine is reduced. Another way of putting it is that the effect is the same as reducing the number of armature turns. In order to bring the effective induction of the main poles up to the required value, more exciting ampere-turns are required. This means that the power-factor of the machine is lowered somewhat by this arrangement.

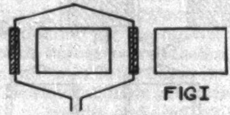


FIG I

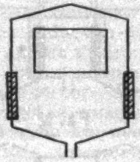


FIG II

In these single-phase motors the object is to get the polar area as large as possible, so that with a given total induction per pole the excitation, or exciting ampere-turns, may be as low as possible. This insures a high power-factor. In Mr. Alexanderson's motor this condition seems to be departed from considerably. In the Siemens-Schuckert motor the commutating pole is placed in the interpolar gap and excited in shunt with the main circuit. This arrangement gives the benefit of the full pitch winding, and the effective polar area is relatively high, possibly 15% higher than in the motor described in this paper. In the motor designed by me the polar area is relatively a little less than in the Siemens-Schuckert, possibly from 3 to 5 per cent.

In reference to frequency, the author says broadly, but without argument, that there is little or no field for the 15-cycle motor. The only basis for this statement is apparently that good commutation is now possible at 25 cycles. In the discussion of the paper by Messrs. Stillwell and Putnam last January, it was not the question of commutation which was advanced as the reason for the adoption of 15 cycles, for it was stated plainly that 15-cycle motors could be made to commutate well. The greatly increased ratio of output to dimensions was given as the principal reason for the adoption of the lower frequency. I see absolutely nothing in this paper to change that conclusion. The motor described this evening, if properly designed, should show just as much improvement at 15 cycles as the series compensated motor; for, as explained before, the use of a lower frequency will allow about 30 per cent. increased induction. In fact, this motor, being worked at a relatively lower induction at start than

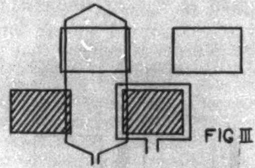


FIG III

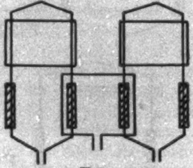


FIG IV

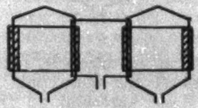


FIG V

the series compensated type, and therefore at less saturation, should show a relatively greater per cent. gain at 15 cycles as regards starting, and when at speed should also show practically the same per cent. gain as the compensated type. Of course this is not on the basis of simply taking a given motor built for 25 cycles and operating it on 15 cycles, which will show a small gain. But the excitation, or exciting ampere-turns, must be increased, and this can be done at the lower frequency without reducing the power-factor; for the inductive volts across the field winding are a function of the frequency as well as of the induction, and thus any reduction in frequency will permit an increase in the induction of the motor. A 30 per cent. increase in the induction of such a motor means a 30 per cent. increase in the counter electromotive force of the armature; and with the same current flowing, the output and the torque are increased at least in proportion to the field strength. It is in this feature of increased induction that the principal gain with lower frequency is to be found. This increased induction is obtained with less short-circuiting in the armature and also with less exciting voltage in proportion to the counter electromotive force, and consequently with higher power-factor. If it were possible to design a 25-cycle motor of large capacity and moderate speed, so that it could be worked at high saturation, then there would not be so much gain in weight and cost by the use of lower frequency, for extra material would have to be added to the magnetic circuit when the induction is increased. But on the larger sizes of 25-cycle motors the iron cannot be worked to high saturations because it is not permissible to put in excitations sufficient to saturate the motor. In fact, it is in general difficult, in such motors, to get in enough excitation for the air-gap alone, unless the field volts are made undesirably high, thus lowering the power-factor. In consequence, on large, moderate-speed, single-phase, 25-cycle motors there is a strong temptation unduly to reduce the air-gap in order to keep down the excitation and thus decrease the size of the motor. In the 15-cycle motor, on the contrary, a considerably larger air-gap can be used than on 25 cycles, due to the fact that there is much more margin for excitation without reducing the power-factor below desirable limits.

If the commutation at speed were the only limit in the 25-cycle motor, then it would be correct to say that with this limit raised sufficiently there would be no necessity for the lower frequency, but as the present limits in design of large 25-cycle motors lie in the excitation permissible with good power-factor, and in the short-circuit voltage at start, it does not seem to me that the problem is solved by simply applying a different method of obtaining commutation when running. The real limits which affect capacity still remain, and I do not see wherein the motor described this evening changes the broad problem in any way. I believe that if Mr. Alexanderson continues his investigations, especially with large motors for heavy railway service, he will be forced to the same conclusions.

**W. B. Potter:** The single-phase motor described by Mr. Alexanderson possesses a number of novel features, but the essence of the improvement is the better inherent commutation. Because of better inherent commutation it is possible to modify the other features affecting the performance of the motors which have heretofore been subordinate to commutation, with the natural result of greater reliability, decreased maintenance, and greater capacity for a given amount of active material.

It is very desirable that the motor equipment of a motor car should be able to develop sufficient torque to slip the driving wheels; for an electric locomotive this is particularly desirable.

Mr. Lamme questions whether a single-phase series repulsion motor will have an output equal to that of a series motor. I call his attention to a recent test of a series repulsion motor having the same armature dimensions and number of poles as the series motor on the New Haven locomotives to which Mr. Lamme refers. I understand that this New Haven motor has a limiting tractive effort of about 5000 lb. The series repulsion motor on the basis of the same diameter of driving wheels gives a tractive effort in starting of 7500 lb. and good commutation up to 75 miles per hour.

An electric locomotive is, figuratively, a draft horse, and its value as such is proportional to the weight on the drivers. In whatever degree the draw-bar pull is limited by the motors, the value of the locomotive, as a tractive machine, is decreased to the same extent. In the handling of any service, sufficient draw-bar pull to start a train is absolutely essential, the horsepower rating for maintaining the schedule being subordinate and depending upon the degree of continuous service. As affecting reliability, the motors are liable to injury from overload unless the load is limited by the slipping of the wheels rather than by the commutation or current capacity of the motors.

With any probable design of motor car or locomotive, the geared series repulsion motor will be able to slip the wheels even if geared for maximum speeds as high as 75 miles per hour. In the light of present knowledge, the problem is somewhat more difficult with the gearless series repulsion motor. With respect to the torque of the gearless motor, the state of the art to-day is not unlike that associated with the geared motor about two years ago.

In the many problems that arise in electric traction, a liberal discount may well be allowed for improvement. For those concerned in development and design, progress in new and untried fields is a privilege and duty, but for those interested only in the earning capacity a conservative attitude will usually best insure economic results. I would not counsel undue caution, but even with the radical improvements which have been made in the single-phase motor, it does not yet follow that single-phase traction is properly applicable to all conditions. A knowledge of the art of compromise constitutes the basis of most of our work, but the equations to be considered are lacking in their most essential feature if they do not contain the dollar sign as applied to each particular problem.

**O. S. Lyford, Jr.:** Many of us thought the repulsion motor dead, and we rather hoped it would stay dead, not that we had anything particular against that type of motor, but because we are beginning to get acquainted with the series single-phase motor which is serving us well. I should like to see one type perfected rather than two or more. If, however, the development of the motor which Mr. Alexanderson has described means a reduction in the cost of single-phase equipment, it will be welcome, as the price of such equipment is now certainly close to the prohibitive limit.

**W. I. Slichter:** The motor described has so many new features in its make-up that it is rather perplexing to grasp the principle of its action as a whole. It may be of interest to discuss these features separately and from a slightly different point of view from that taken by Mr. Alexanderson. In explaining the motor it is necessary to consider separately, the conditions of starting and running, as certain features are introduced simply to assist in starting, and other features are employed only to function when running.

*Starting.* In all single-phase commutator motors there is a definite value of the flux per pole above which it is inadvisable to operate, since the electromotive force of transformation in the short-circuited coil undergoing commutation becomes so great as to give unsatisfactory commutation. This limitation is particularly strict at starting, when the armature is at rest or moving very slowly. As the motor speeds up it would be possible to use a higher flux value; first, because each coil is under the brush for a shorter period; secondly, because there are various means of counteracting the electromotive force of transformation by devices dependent upon the speed of the armature.

But in all series type motors the natural characteristics involve a decrease in current with increasing speed, and hence a decrease in flux. If, therefore, a motor is designed with a proper value of flux at starting, it will have too little flux at running; if with a proper value at running conditions, it will have too great a flux and bad commutation at starting. This limitation does not prevail in direct-current motors, since any value of flux may be used without harmful effect.

In the motor under discussion the compensating or inducing winding and its inductive relation to the armature turns are made to act as a series transformer. By winding the compensating winding with twice the number of turns as are on the armature, there will be twice as much current in the rotor as in the stator when the rotor is short-circuited, and the same current in both members when the rotor is open-circuited. This gives an approximation of the ideal conditions in a single-phase commutator motor—that of operating at all speeds with the strongest field compatible with good commutation.

*Running*. Under running conditions we find in this motor three very important new features contributing to good operation.

1. The proper field strength at all speeds, as just mentioned.
2. By means of a fractional pitch in the armature (Fig. 1), the coil undergoing commutation is placed in a position under the pole piece, where it is very strongly influenced by any magnetomotive forces in the compensating winding, so that the latter winding is able to act as a real commutating pole as well as a compensating winding.
3. The compensating winding is made to carry two components of current—a series current and a shunt, or repulsion motor current. It may be likened to a commutating pole having two coils, one a series coil serving very effectively, due to the favorable position of the coil undergoing commutation (brought about by the fractional pitch), to produce the good effects on commutation that a commutating pole does in a direct-current motor; in other words, to correct for the harmful electromotive forces of self-induction and armature reaction. This is accomplished by making the compensating winding stronger than the armature winding, thus the excess of compensating winding magnetomotive force sets up a local flux at the corners or tips of the poles which becomes a commutating pole.

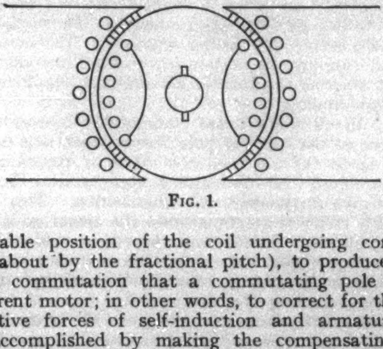


FIG. 1.

The shunt coil, shunt component of current or repulsion motor current, corrects or reduces the electromotive force due to transformer action in the coil undergoing commutation by a happy combination of phase relations, as shown by the following vector diagram, (Fig. 2).

$E_0$ is the line or terminal voltage of the motor.

$I_0$ is the series-load current of the motor lagging behind $E_0$ a small amount, as in normal running conditions.

$\phi_m$ and $\phi_c$ show the time-phase-position of the two fluxes, motor and compensating, produced by $I_0$. These have different space-positions.

$e$ shows the harmful electromagnetic force of transformation in the short-circuited coil, 90° behind $\phi_m$, because $\phi_m$ produces it by induction.

A portion of $E_0$ is now impressed across the compensating winding in shunt, producing a flux $\phi_1$ 90° behind $E_0$. But the compensating winding is wound opposed, or 180°, to the armature winding which throws this flux down to $\phi_2$.

The armature coil moving in this flux has generated in it by rotation an electromotive force, $e_2$, in phase with $\phi_2$ which is approximately opposed to $e$, combines with $e$ to make the resultant $e_3$, which is of very small magnitude and of such phase as to be subject to the corrective influence of the flux $\phi_c$ of the ordinary compensating winding.

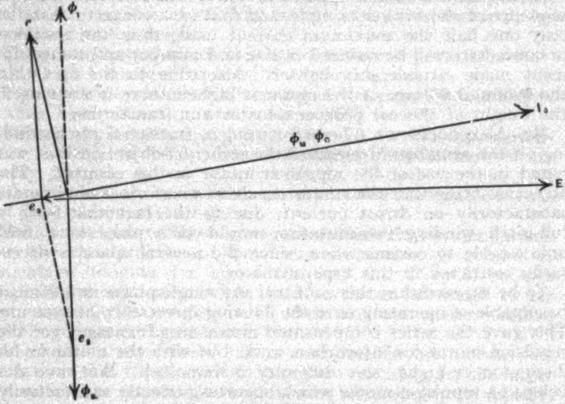


FIG. 2

The final result is that the commutation troubles of the single-phase commutator motor are corrected in the logical way of removing the cause instead of the half-hearted way of reducing the effect, as is done with high-resistance leads.

A certain number of wattless volt-amperes are consumed in producing this effect, but a considerable amount of energy is saved and removed from a place which is particularly sensitive, the commutator, and a very large saving is effected in maintenance.

One of the immediate results of the development of this motor is the fact that it makes the need of 15 cycles for single-phase railway work a great deal less important than with either the plain repulsion motor or the plain series motor. As brought out in the discussion of Messrs. Stillwell and Putnam's paper, the greatly increased cost of generators and transformers at 15 cycles is a considerable handicap to that frequency, and with the former types of motors a 15-cycle system showed a lesser cost only in very heavy work where a large number of heavy motors were required. With the new motor, a considerable portion of the field of the 15-cycle motor has been conquered, and although the new motor is slightly better at 15 cycles than at 25 cycles, it will probably be found that there are very few cases where any 15-cycle motor and its transformer will weigh or cost as little as this type of motor and transformer at 25 cycles.

In the control of this type of motor it will be noted that the sequence of steps is very simple, and that each contactor handles only one half the maximum current used, thus the switches or contactors will be reduced in size and number and the equipment made considerably lighter. Also, due to the fact that the terminal voltage of the motor is higher, there is a saving in the weight of the car compensator or autotransformer.

Mr. Alexanderson's scheme of using a fractional pitch winding on the armature overcomes the principal objection that was found in the use of the repulsion motor in this country. The objection being that the simple repulsion motor does not operate satisfactorily on direct current, due to the fact that with a full-pitch winding commutation would take place in a field unfavorable to commutation, since the neutral space is necessarily restricted in this type of motor.

To be successful in this country, any single-phase motor must be capable of operating over the existing direct-current systems. This gave the series compensated motor an advantage over the repulsion motor for interurban work, but with the motor under discussion to-night, this difficulty is removed. We have developed a repulsion motor which operates perfectly satisfactorily on direct current.

**S. M. Kintner:** I am disappointed because Mr. Alexanderson has not told us more about the behavior of the motors in actual service. The theory is nicely worked out, but I for one would be better satisfied with less theory and more matter of a quantitative nature. For instance:

1. What is its power-factor?
2. How does it compare in weight with standard direct-current motors of equal torque?
3. How does its commutator wear in service requiring frequent acceleration with large torque and corresponding heavy currents?
4. What character of brush is used, and what life in car-miles is obtained?
5. How long can it stand locked with 150% full-load torque?
6. How does it stand sustained overload torques of 150 per

cent.—200 per cent. of the hour ratings, for periods of 3 or 4 minutes, when operating at normal speed and also at very low speeds?

The above conditions are the critical ones in the operation of single-phase motors, and it is upon their ability to stand such tests and service that their value should be based. Mr. Alexanderson's commutating-pole motor will probably give good commutation when running, but so will any well-designed series compensated motor with preventive leads. It is not the running but the starting condition that is the troublesome one; it is then that motors with preventive leads show their greatest superiority over those without them. The proposed method of obtaining improved running commutation is of questionable value when it is obtained, as Mr. Lamme has pointed out, at the sacrifice of starting torque and power-factor or by increase of motor weight.

The power-factors of a certain line of series compensated motor, with which I am familiar have the following values:

Twenty-five cycle motors, varying in size from 75 to 250 h.p. at their hour ratings, power-factor = 85% to 90%.

Fifteen cycle motors, varying from 75 to 500 h.p. power-factor = 88% to 94%. Some of these 15-cycle motors are simply 25-cycle motors adapted to the 15-cycle service. All of these values are taken from motors having reasonable speeds and good commercial air-gaps.

Data on weights on those same motors show that in comparison with the standard line of direct-current motors on a basis of percentage weights for equal torques, the 25-cycle motors weigh 33 per cent. more, while the 15-cycle motors weigh 10 per cent. more. The weights in all these are total motor-weights, including gears and gear-cases.

In checking over these values a noticeable matter was the limitations that the 25-cycle motors were reaching; for the larger size motors the percentage weights were increasing quite rapidly. This was not noticeable within the limits checked on the 15-cycle motors. This limit in the 25-cycle motor is caused largely by the increase in iron necessary to keep down the inductive element and consequently secure a reasonable power-factor.

Recent calculations show that in a given space it is possible to get a 500-h.p. motor on 15 cycles, but the best that could be designed for equally good performance on 25 cycles was 360 h.p. From this it is evident that 39 per cent. greater output is possible in the same space with 15 cycles. This indicates very clearly the need of 15 cycles for the heavier class of service.

The motor described by Mr. Alexanderson is limited in precisely the same manner as the series compensated type, and at smaller ratings. It will also be benefited, so far as output for a given weight is concerned, by the use of 15 cycles.

In dismissing the question of 15 cycles, Mr. Alexanderson admits that for large gearless motors for high-speed service there is an exception. Why except this class of service? Is commutator speed the reason?

A comparison of two 4-motor equipments made up of 75-h.p. motors at 25 cycles and the same motors adapted for 15 cycles giving 95 h.p., shows very clearly the gain in tractive effort and horse power possible with the 15-cycle motors. The total electrical apparatus per car was but 5 per cent. heavier with the 15 cycles, but the gain in horse power was 26 per cent. On a basis of total car-weights, the differences were 1.6 per cent increase in weight on 15 cycles and a gain of 26 per cent. in horse power.

The commutator wear in service requiring frequent and rapid acceleration is a serious one. A commutator that will not take a gloss, will rapidly consume brushes and soon go to pieces. If the currents are heavy at starting, and the starting frequent, the commutator is apt to have copper drawn from bar to bar and thus short-circuit certain coils. To show the limitations of a motor of this character, a test should be conducted as follows: the motor should be mounted on a shaft driving large fly-wheels, the inertia of which corresponds to that of heavy cars accelerating from rest. The control should be arranged so that as the wheels are accelerated the proper sequence of switch operations and voltages is applied to the motor. When a predetermined speed is reached, the power is cut off and the motor allowed to coast for a fixed time, when brakes are applied and the wheels brought to rest. This same cycle is repeated automatically by a motor-driven control, the single-phase driving motor being thus subjected to a service more severe than any it is apt to meet in operation on a car. This is an excellent test of the motor's ability to stand heavy currents while at rest, also while accelerating slowly, as it is connected rigidly to the shaft and gets the full force of the first rush of current.

This test should be continued for a week or more. The current used should be much in excess of the motor's ratings, and forced air will be necessary to keep down the temperatures to safe limits. The test is not one of temperature, but one of commutation under abnormal service conditions.

This test is also quite effective in determining carbon-brush characteristics. Within the last few days I have compiled some data gathered from a road operating approximately 100 motors of this kind, each of 100-h.p. capacity. This road reports the car-miles per brush as follows:

| October | November | December | Average |
|---|---|---|---|
| 14,600 | 15,550 | 15,450 | 15,200 |

The motors from which these data were taken are in very hard service, the cars averaging over 200 miles per day. On one run the car is compelled to make 583 miles per day. During October one car ran 10,740 miles; during November, 9,400 miles. Another road using similar motors reports approximately 13,000 car-miles per brush as the average for the last two months.

These motors have all been in operation over a year and have brushes of a medium grade, such as are used on direct-current motors and generators.

The ability of motors with preventive leads to stand excessive overload torques when locked for periods of 10 or 15 seconds has been demonstrated repeatedly by testing them after being on cars or installed on locomotives. These tests have been made by applying power with the brakes locked, and at other times by attempting to pull trains upon which the brakes were not released. The requirements of overload are largely at starting; they are not so important when running. During the last year and a half I have followed closely the operation of about 600 of these motors; I do not recall a single case of trouble that could be traced to a preventive lead burning out.

While many may look upon preventive leads as a luxury, in my opinion they supply the most economical design possible with single-phase motors in the present state of the art. I believe that they will continue to be used until some one devises a motor that is not subject to the short-circuit action in starting, as well as in running. Mr. Alexanderson's motor does not fulfil this requirement, and I see no reason why it could not be improved by adding preventive leads.

Mr. Potter says that with the Alexanderson motor it is feasible with motors of the same dimensions to get 50 per cent. more tractive effort than that of the New Haven motors. So long as the torque of motors depends upon the number of conductors on the armature, the limits of which are determined by the size of commutator with reasonable bar-width; secondly, upon the induction per pole, which is admittedly lower than that in the New Haven motor; and, finally upon current—my opinion is that it cannot be done with reasonable currents for the possible size of commutator.

**Chas. P. Steinmetz:** It is true and has been well known since the early days of electrical engineering, that any direct-current motor can operate on alternating current if its magnetic field is laminated so as to be responsive without excessive loss to rapid alternations of magnetism. But there were two great objections to this motor, both well recognized in the art before any extensive work was done; these objections were impracticably low power-factor and hopelessly bad commutation. I remember reading as far back as 1889 in Mr. Gisbert Kapp's at that time classic booklet on alternating-current machinery, the proof that the single-phase alternating-current motor can never be of any practical use, because its power-factor must be too low for practical use. The first problem that had to be solved in getting an operative motor was to raise the power-factor to practical values. This was undertaken and solved about eighteen years ago by Rudolf Eickemeyer, who gave us the compensating winding, which is now used in all single-phase alternating-current motors. He recognized that to give a good power-factor, the single-phase commutator motor must have few field turns, many armature turns; that is, a weak field with a strong armature. To be able to use these proportions, the armature reaction and self-induction must be neutralized by a compensating winding; a coil surrounding the armature as closely as possible and energized either by the main current in series and in opposite direction to the armature current, or closed upon itself and energized by its secondary induced current. Eickemeyer gave us both types of operative alternating-current commutator motors, the conductively compensated, and the inductively compensated. Thirteen years elapsed before the electrical industry caught up with Mr. Eickemeyer's work, and the compensated series motor was applied to commercial service.

Independent thereof, and starting even earlier, an apparently entirely different type of motor was experimented upon and designed by Elihu Thomson. This was the so-called repulsion motor. On converging lines these two motors have continued throughout the intervening period, until now in Mr. Alexanderson's series repulsion motor they merge into one. Mr. Alexanderson's motor is not a compromise between the two types of motors, but a modification of the repulsion motor so as to give at all speeds the perfect commutation that the repulsion motor has only at synchronous speed; that is, perfect commutation at all speeds by producing the condition of synchronous commutation at any desired speed.

After Mr. Eickemeyer's work was concluded, and the compensated series motor had arrived, there remained the problem of commutation, which has been the great problem of the alternating-current railway motor during the last few years, although frequently it has been more or less hidden under statements regarding size, weight, etc. Looking into the design of the compensated series motor, it will be found that there is no other inherent reason why it should differ essentially in weight or size or capacity from the direct-current motor, if it were not for the severe limitations in the design imposed by the problem of making the commutation sufficiently good not to be self-destructive in too short a time. The problem of getting reasonably fair commutation means that the alternating-current motor has to be designed with eight or twelve poles, where the direct-current motor would have four or six poles. It means that the alternating-current motor has to be supplied with a very large commutator to receive current at 150 or 200 volts, while the direct-current motor commutates much smaller currents at 500 and 600 volts. It is as easy to insulate 600 volts alternating current as 600 volts direct current, and so nobody would choose such large low-pressure currents and bulky commutators if not forced to it by the problem of commutation. So weight and size must be sacrificed to get moderately reasonable commutation. Some advantage is gained by the introduction of high resistance or high inductance leads. It must be realized, however, that the high resistance or high inductance leads, suggest, in a measure, the old saying, " Out of the frying pan into the fire." Reducing the short-circuit current by interposing resistance or inductance results in a drop of potential across the resistance or inductance which appears at the edge of the brush when the brush leaves the commutator segment. So sparking can not be entirely stopped by this means. The logical way to improve commutation is to remove the cause of sparking, the short-circuit current under the brush.

Some years ago one of my assistants, Mr. Milch, investigated the short-circuit current under the brushes, and found that it could be eliminated by impressing a commutating field upon the motor at the commutation point, or in quadrature with the main field. By giving the compensating winding more ampere-turns than the armature, or by using a series commutating pole or an interpole arrangement that works successfully in the direct-current motor—the commutation of the single-phase alternating-current motor cannot be improved, because the alternating current has an intensity as well as a phase, and the magnetic flux of the inter-pole being in phase with the main flux and main current, is wrong in phase. A commutating flux is necessary; a flux that differs in phase from the main flux, and is approximately in quadrature therewith. The production of such a magnetic flux, or a true commutating flux varying with the speed in the proper manner and differing in phase from the main flux, is what makes this series repulsion motor commutate perfectly at all speeds.

Another valuable feature of Mr. Alexanderson's work is the investigation of the distribution of the magnetic field. It is not sufficient merely to have the two quadrature components of the magnetic field of proper intensity and proper phase; what is essential in commutation is not the total quadrature field, but the field at the point where the brushes stand. This fact made it necessary to investigate the local distribution of the magnetic field over the armature circumference. The result of this work, then, eliminated the question of commutation from the alternating-current single-phase motor at all speeds.

It is true that at standstill the short-circuit current is still there, and must always be there, except that it may be interchanged against voltage by inserting resistance or inductance. It must not be overlooked, however, that the harmful effect of the short-circuit current is a function of the product of the current and the time during which the current exists; in this respect a motor in which the short-circuit current practically disappears at extremely low speeds has the advantage over a motor in which the short-circuit current retains the same relative proportion to the main current throughout all the speeds up to the highest. I believe this feature is the explanation of the great difference between Mr. Lamme's theoretical conclusion and Mr. Alexanderson's practical experience on one and the same size of motor.

It appears to me, therefore, that the second and last serious problem of the alternating-current motor which still remained after Eickemeyers work, the problem of commutation, has finally been solved by the work recorded in the paper before us. The alternating-current single-phase motor is in practically as good a shape as the direct-current motor, and I may perhaps say that with this work the second period in the development of the alternating-current railway motor, the period of youth, is concluded.

**W. S. Murray:** It is better to eliminate the cause of, rather than remedy, a deleterious effect. Thus an arrangement which naturally produces a proper commutating flux without especially providing extra means for it (such as commutating poles) is certainly a most valuable point gained.

Again, the elimination of resistance leads on account of the elimination of the cause requiring them is a welcome characteristic. We are all aware of the advantages, in high powered electric locomotives, of gearless construction; we are likewise aware, in this form of construction, of the high ratio of weight on drivers to tractive effort developed with alternating-current motor construction. In consequence of this unfortunate relation, should the entire electric locomotive weight be on drivers, it is impossible to design the motor equipment of sufficient capacity to slip the wheels of the locomotive; and as the transformer action is a maximum at starting, unless the locomotive enigneer shuts off power promptly upon finding the locomotive incapable of moving its trailing load, the resistance leads will burn out.

Mr. Alexanderson gives the general superior characteristics of his motor over those of the repulsion type. Since the introduction of the series compensated motor, I had been under the impression that the repulsion type could hardly be considered a competitor, due to the bad operating characteristics above synchronous speed, as explained in Mr. Alexanderson's paper. This new type of series-repulsion (which by the way might have its name reversed and be called repulsion-series, as it has to start before it runs) combining the good characteristics of the repulsion type for starting and the good characteristics of the series type for running, brings about a worthy competitor and lifts the mark of alternating-current traction to a higher notch.

Alternating current no longer recognizes direct current as a competing agent in the transfer of power. Commercially, they are in limitation to each other in this respect from a unit point of view in the ratio of 1 to 10,000; and so even though low transmission losses by alternating-current transmission may compensate for increased costs of traction apparatus, with its attendant lower efficiencies and greater non-revenue weights, it is a welcome sight to observe the alternating-current motor designer, not satisfied with this, but setting up for his model of accomplishment a motor the equal in every respect to its direct-current confrére.

The feature of producing double torque at starting by short-circuiting the armature and without increasing the line current is a characteristic that lends itself in much value to traction necessities. Although the point is not brought out, I assume that this arrangement prescribes that the motor operates at half of what the speed would have been had the short-circuit not been applied to the armature. In this connection it would be interesting to know what change of relation takes place between time and the temperature of the motor when developing double torque, also how the power-factor of this motor compares with that of the series compensator type for starting and low-speed conditions.

It would be interesting, further, to know how the weight per axle horse power one-hour rating compares with direct-current motors of the same size, also what the ratio of hour to continuous capacity prevails in this class of motor.

**E. F. Alexanderson**: In answer to Mr. Stillwell's question whether the increased capacity in changing from 25 to 15 cycles applies in the same rate to the series repulsion as to the series motor, it can be said that if the heating of the motor is the limitation, it does not apply; if the starting torque is the limitation, it does apply. In the case of a motor that can slip its wheels, the heating is the limitation; in that case the 15- and 25-cycle motors have virtually the same output.

A direct-connected motor may be called upon to give higher torque than is practical to obtain on 25 cycles, and in this case the ratio holds.

I thoroughly appreciate Mr. Lamme's contention that resistance leads increase the torque of the series motor by allowing the increase of the flux which is one factor necessary to torque. The other factor is the current, and by changing the ratio of excitation the current can be increased more than the flux could be increased by the use of resistance leads. The motor gives double torque with normal flux, and double current and normal torque with 70% flux and 140% current. The cross-currents in the brush may seem excessive, but they do no harm.

On a 50-ton locomotive that has been in service for half a year, hauling trains of about 400 tons, the motor slips its wheels without damage to the commutator, although it has not the improved arrangement for starting referred to in this paper.

Mr. Lamme made particular reference to the New Haven motor with a rating of 250 h.p. at 220 rev. per min. for one hour. I am familiar with this motor, because I have designed a repulsion motor for the same purpose with the same outside dimensions. This motor has been tested and has an output of 280 h.p. continuously, and 350 h.p. for one hour at the speed indicated by Mr. Lamme. This increase from 250 to 350 h.p. at the hourly ratings of the two motors is fully as high as the increase claimed by changing from 25 to 15 cycles.

A higher output can be obtained from the series repulsion motor for the same reason as in the 15-cycle series motor, by working the iron to saturation. If the higher flux were obtained by increasing the field turns, the effect would be, as stated by Mr. Lamme, a decreased power-factor. The power-factor, however, does not depend upon the number of ampere-turns in the field, but upon the ratio between excitation and armature reaction. By abolishing the resistance leads and allowing more room for copper, the armature reaction can be increased simultaneously with the field excitation and without affecting the power-factor, and the increased output is gained by increased voltage as well as increased current.

Mr. Kintner gave some data on the wear of brushes. A number of equipments of this type have been in operation for some time, but I am sorry that I cannot give the ultimate life of brushes, because they have not yet worn out. Brushes that have been in service for 10,000 miles show a wear of $\frac{3}{16}$ in. and the brush looks like new, so that there is no other limitation to the life of the brush than the amount that it can be fed down in the holder. The commutator assumes a brown polish like that of a good direct-current motor.

**Elmer A. Sperry** (by letter): It seems to me, that Mr. Alexanderson's paper indicates an epoch-making advance in the art of railway-motor design. In connection with the remarks that have been made in reference to slipping versus non-slipping drivers, if I understood the remarks correctly, it was stated that the dead weight of the equipments for heavy traction work range so high that it is impossible to get motors with power enough to slip the drivers sustaining these weights. I take this theory of the locomotive to be almost revolutionary. I think there is no railroad superintendent who would consider a steam locomotive that could not easily slip her drivers as worth putting a fire into. I have been engaged for some years in designing and manufacturing locomotives for the most strenuous sort of work, and I remember reading a paper before this Institute about fifteen years ago, describing some aspects of these machines. I most cordially agree with Mr. Potter, that one of the most essential features, and one which must not be neglected in the design of a successful electric locomotive, is that it should be possible at all times to slip the drivers, even under conditions of heavy sanding. In this connection it might be stated that if it is considered important for the steam locomotive, it is certainly doubly so for the electric locomotive, where slip is necessary as a preventive of excessive overloading of the motors; this is a consideration of importance to us, but a point that does not in the slightest affect our competitor, the steam locomotive.

Several years ago we started to build rack-rail locomotives, principally for mine haulage. Since that time we have installed several hundred miles of this equipment and new installations are going on constantly. Here there is no safety-valve for the electric motor, no slipping has been possible, and we have had no little difficulty in adapting motors to this service. They have had to be designed and re-designed until a successful machine of to-day is, in case of emergency, able to slip the drivers, including the pinions up out of the rack, without damage to the motor. Leaving the rack occurs at a point between 180% and 200% of draw-bar pull.

I would emphasize what I have said, and add a note of warning to the designing engieer: a locomotive that can not slip its drivers will not be able to stand in competition with one designed easily to accomplish this function.

**E. F. Alexanderson** (by letter): Regarding Mr. Lamme's remarks concerning the use of resistance leads, I would say that in the series motor the function of the resistance leads is dual; first, to assist in commutation, and secondly, to help in starting. In the series repulsion motor the problem of commutation has been solved, and therefore the only field of usefulness for these leads would be at starting. If resistance leads were the only solution to obtain good starting, they would be used in the series repulsion motor, as series repulsion motor with resistance leads would give the same increase in rated capacities, and the same improvement in commutation, as would be effected by changing the frequency of the series motor from 25 cycles to 15 cycles.

The above statements are verified by actual tests. Messrs. Lamme and Storer have given examples of tests before the Institute, which show that a 100-h.p., 25-cycle series motor when operated at 15 cycles is rated at 125 h.p. Other tests have been made on a 75 h.p. motor operating as a series repulsion motor at 25 cycles, and operating as a series motor at 15 cycles. The results of these tests show that the heating was lower in the former than in the latter instance. Another series repulsion motor of 450 h.p. continuous output when running at 400 rev. per min. showed that the heating was only 5° cent. higher when operated on alternating current at 25 cycles than operated on direct current.

The characteristic curves given in Fig. 1 relate to the last named motor, and it may be of interest to state that this same machine has delivered 800 h.p. at 310 rev. per min. with almost sparkless commutation. An examination of the power-factor curve shows that its general nature varies somewhat from that of the series motor in being more constant through its entire range of operation, and it gives a speed curve more nearly resembling that of the direct-current motor than can be obtained with the series motor.

As this power-factor ranges from 90 to 94%, it certainly does not need to be apoligized for, as some the other speakers seem to think. If my remarks in the text of the paper are taken as apologetic, I must explain that I was comparing the power-factor of the series repulsion motor with that of the Latour-Winter-Eichberg motor, which at least is worthy of as much consideration as the series motor.

In answer to questions about the ability of the series repulsion motor to exert a torque at standstill, I reply that motors have been tested with the armatures blocked and have given double their normal torque for one minute. A large number of series repulsion motors are in operation without resistance leads and no difficulty has been experienced in starting, although these motors have not the improved features of starting which are referred to in the paper.

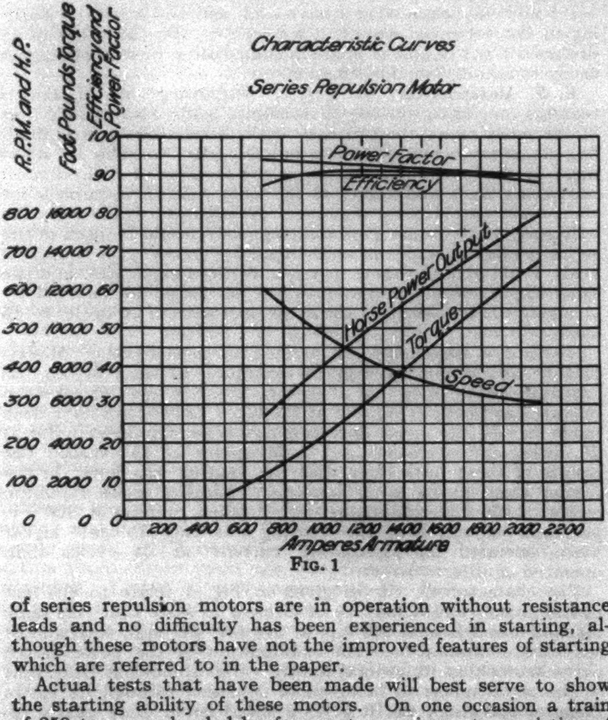


Fig. 1

Actual tests that have been made will best serve to show the starting ability of these motors. On one occasion a train of 250 tons was hauled by four-motor equipments consisting of 125 h.p. motors. This train was started on a one per cent. grade, and as a further test two motors were cut out and the remaining two motors started this 250-ton train on the same grade.

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# THE NEW HAVEN SYSTEM OF SINGLE-PHASE DISTRIBUTION WITH SPECIAL REFERENCE TO SECTIONALIZATION.

BY W. S. MURRAY.

The method and distance chosen for sectionalizing the high-tension wires supplying power for alternating-current traction is worthy of careful consideration. Local conditions play so important a part in the correct conclusion of method and proper distance to be applied, that no precedent or convention can be followed and standardization is quite out of the question.

In advance of taking up the concrete subject at hand, doubtless it will be of interest to touch upon several alternative distributing systems that were considered by the engineers of the New Haven road before the final adoption of the system of single-phase distribution and sectionalization now in service. Some of these were:

1. 11,000-volt, three-phase generation at the power house; transmission along the right-of-way at this voltage; step-down transformers furnishing trolley voltage at 3300; track mileage divided into three equal linear parts, each part being supplied by an individual phase.

2. The same arrangement as (1) with the exception that step-down transformers furnish 6600 volts to trolley.

3. 11,000-volt, three-phase generation at power house; transmission along the right-of-way at this voltage; track mileage divided into two equal linear parts, each part having its trolley connected through the transmission line to one of the three terminals of the power-house bus-bars, the remaining

bus-bar being connected to the tracks, thus making a common connection for the two trolley sections.

Diagrams 1, 2, and 3, Fig. 1, represent in the simplest form the three above described arrangements. It follows, of course, that

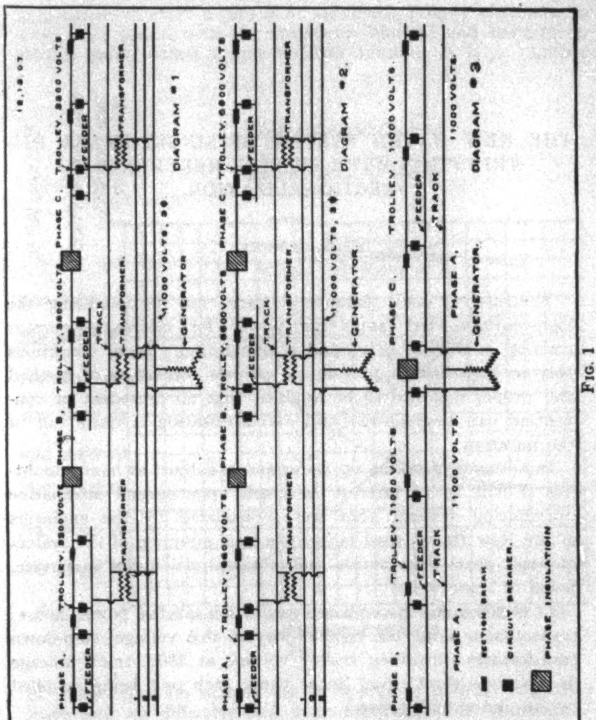
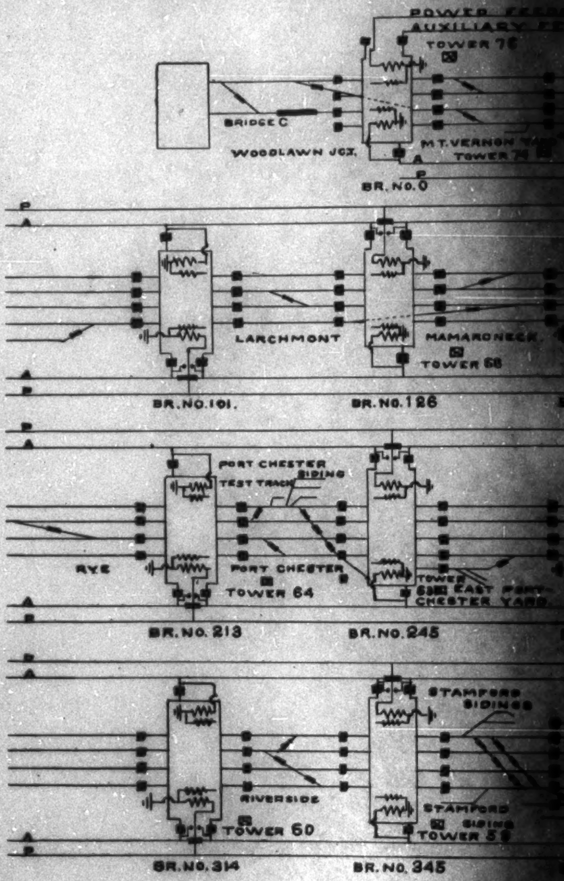

12, 13, 07
PHASE A, TROLLEY, 3300 VOLTS
PHASE B, TROLLEY, 3300 VOLTS
PHASE C, TROLLEY, 3300 VOLTS
FEEDER
TRACK
TRANSFORMER
11000 VOLTS, 3Φ
GENERATOR
DIAGRAM #1
PHASE A, TROLLEY, 6600 VOLTS
PHASE B, TROLLEY, 6600 VOLTS
PHASE C, TROLLEY, 6600 VOLTS
FEEDER
TRACK
TRANSFORMER
11000 VOLTS, 3Φ
GENERATOR
DIAGRAM #2
PHASE B, TROLLEY, 11000 VOLTS
PHASE A, 11000 VOLTS
PHASE C, TROLLEY, 11000 VOLTS
FEEDER
TRACK
PHASE A, GENERATOR
11000 VOLTS
DIAGRAM #3
SECTION BREAK
CIRCUIT BREAKER
PHASE INSULATION

FIG. 1

the phased divisions in each case could be further individually subdivided into sections wherever desirable. The presentation of these three methods of distribution by no means prescribes the limit of combinations that mav exist, as many others of an interesting character have been suggested.

DISTRIBUTION SYSTEM, WO


POWER FEEDE
AUXILIARY FE
TOWER 76
BRIDGE C
WOODLAWN JCT.
MT.VERNON YA
TOWER 74
A
P
BR. NO. 0
P
A
LARCHMONT
MAMARONECK
TOWER 68
A
P
BR. NO. 101.
BR. NO. 126
P
A
PORT CHESTER
SIDING
TEST TRACK
RYE
PORT CHESTER
TOWER 64
TOWER
63 EAST PORT-
CHESTER YARD
A
P
BR. NO. 213
BR. NO. 245
P
A
STAMFORD
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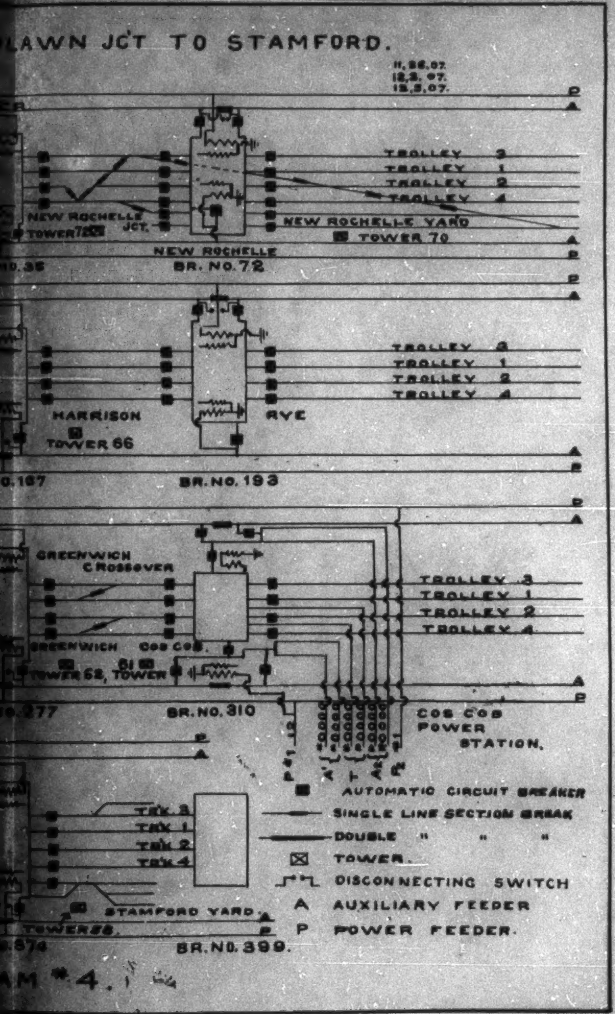
P
BR. NO. 314
BR. NO. 345

DIA


LAWN JC'T TO STAMFORD.

AM #4.

11, 26, 07.
12, 3, 07.
12, 5, 07.
P
A
TROLLEY 3
TROLLEY 1
TROLLEY 2
TROLLEY 4
NEW ROCHELLE TOWER 72
NEW ROCHELLE JCT.
NEW ROCHELLE YARD
TOWER 70
NEW ROCHELLE
BR. NO. 72
NO. 35
HARRISON
TOWER 66
RYE
BR. NO. 193
O. 167
GREENWICH CROSSOVER
GREENWICH
TOWER 62
COS COB
61 TOWER
BR. NO. 310
O. 277
COS COB POWER STATION.
TR'K 3
TR'K 1
TR'K 2
TR'K 4
STAMFORD YARD.
TOWER 58.
BR. NO. 399.
.374
AUTOMATIC CIRCUIT BREAKER
SINGLE LINE SECTION BREAK
DOUBLE " " "
TOWER.
DISCONNECTING SWITCH
A AUXILIARY FEEDER
P POWER FEEDER.

(Murray)

4. 11,000 volt, three-phase generation, transmission along the right-of-way at this voltage, only one phase being applied to all sectionalized trolley wires throughout the zone of electrification. The three phases are also carried throughout the electrification zone, and are at all points available for polyphase motors, such as would be used in railway machine shops and for the operation of motor-driven generators in local direct-current railway plants owned by the railroad company.

In Diagram 4, Fig. 2, there is shown diagramatically the actual scheme of single-phase distribution which has been adopted, and is now in service.

There are advantages to be gained in any one of the above mentioned alternatives, but the single-phase distribution as described under 4 carries with it advantages, the sum of which far outweighs the sum of the advantages in the others. In a word, the distribution, as described under 1, 2, and 3, would seem to offer a better opportunity to distribute the load in the three-phase windings of the generators, and yet this is open to question on account of the possible unequal distribution of trains in the individual phased sections; but the greatest and deciding disadvantage to any of the three-phase distribution schemes is the complication that results in the overhead system, together with the fact that for an equal weight of overhead copper the efficiency of the single-phase system is higher than any of the polyphase arrangements. From the foregoing, I believe it will be generally conceded that the single-phase scheme of distribution is the best.

A modification of arrangement 4, which was considered, may be mentioned; namely, 11,000-volt, three-phase generation, single-phase distribution for traction with step-down transformers distributed along the line, their secondaries furnishing 3300 or 6600 volts to the sectionalized trolleys. For the reason that the life-hazard in using 11,000 volts was not considered to be greatly increased over that of 3300 or 6600 volts, and in view of the higher efficiency, lesser currents to be collected by locomotive shoe contacts, greater reliability, and the lower operating costs (no transformer sub-stations) the advantages of the 11,000-volt direct transmission to the sectionalized trolleys was immediately apparent, and the problem became simply one of insulation.

As concerns the choice of three-phase generators in connection with single-phase distribution for traction purposes, again local conditions were the real factors that framed this conclusion. Single-phase or balanced polyphase voltages are undeniably more desirable than unbalanced ones; at the same time when proper allowance and arrangement are made for the unbalanced voltages, and there is a decided market for polyphase power, it is difficult to escape the conclusion that it is a desirable and necessary adjunct to the system. In connection with its application to the New Haven electrification, it may be said that synchronous motors will be shortly substituted for steam engines in one of our lighting plants. Such arrangements will bring about the centralization of power generation, and by proper field adjustment of the synchronous motors the general power-factor of the single-phase system will be raised.

Having touched upon some of the determining factors that brought about the arrangement of three-phase generation and single-phase distribution, the remainder of this paper will be confined to a discussion of the methods and lengths involved in the sectionalizing of the single-phase distribution, and as the power wire (which is the outside wire marked *P* in Fig. 4) plays only an unimportant part in its applications to the traction system, it will not be referred to again.

An examination of the electrical connections made in and on the power-house, line, and locomotives would bring out the strong similarity of the New Haven System to the well standardized direct-current, (not alternating-current–direct-current) system. Indeed, I think it can be fairly said that the current in either case has the same path to follow, the only differences lie in the nature of the current (alternating and direct) and the voltage. In either case the path is from one bus-bar of the station to the feeder and trolley, thence to the locomotive and from there to the rail and return to the other station bus-bar. In the alternating-current system is noted, of course, methods of installation common to high-tension practice.

Single-phase distribution offers an excellent opportunity for sectionalizing. As may be seen in Diagram 4, Fig. 2, the system consists simply of the track trolleys, two auxiliary wires immediately adjacent, and the necessary switching complement. Although these auxiliary wires have been called feeder wires and while, as a matter of fact, they do serve to increase the capacity of the overhead system, this is not their principal function, as the amount of copper included in the trolleys would suffice to be within the economic figures of copper loss. The auxiliary wires are installed to serve as by-passes, in the event of it being desired to cut dead any or all of the trolley wires in any section. Thus by this system of auxiliary by-passes any degree of sectionalizing can be used, and any or all trolley voltages in sections can be removed without interrupting the continuity of the voltages throughout the zone.

The lengths of sections are governed entirely by local conditions. No two sections of the 14 that exist in the 21 miles of New Haven electrification are the same. It is seen, however, from these figures that the average length of sections is 1.68 miles, that none of these is over 2.19 miles or less than 1.07 miles.

The best reason that can be assigned for the use of sections is in order that line troubles may be localized. There are many others, and some of a most important character. Indeed, it may be said that were the line absolutely immune from trouble, such as grounding, mechanical failures, etc., there would still be many good reasons for sectionalizing it, and these reasons will develop as the subject is further studied.

One of the most attractive features of single-phase distribution is the elimination of sub-stations with their fixed and operating charges, and unlike the alternating-current–direct-current scheme of distribution, where the length of section is settled by the equation of load and copper to meet it, the single-phase system is not bound by these limiting electrical conditions. Line-loss is forgotten in the establishment of a mechanical construction, the amount of copper in which is only a fraction of the amount required for an equivalent loss for the same amount of power transmitted in the alternating-current–direct-current systems. This convenience of transmission with low loss permits sectionalizing *ad libitum* and the local conditions are accorded almost the entire privilege of decision. The advantage of such a relation between operation and distribution was immediately apparent to Mr. E. H. McHenry, Vice-president of the New York, New Haven & Hartford Railroad Company, whose suggestion that the electrical and train signal blocks be made co-terminus was adopted. It will be noted, then, that of the fourteen electrical sections between Woodlawn and Stamford, nine of these are co-terminus with the signal towers. In each of these towers, there is installed a small panel containing the pilot-switches controlling the trolley (and by-pass) circuit-breakers installed on the anchor bridges. Aside from the economical features of this scheme of control, as no operators other than our present signal operators are required, the value of placing the distribution in the hands of this class of men is most important, their constant attention to matters pertaining to the operation of trains bring about the attention which should be accorded to the distribution of current; their thorough understanding of the conditions of traffic on the various tracks permitting the most intelligent handling of electrified and de-electrified trolleys, assuring at once prompt and reliable service in the matter of handling a situation when cross-overs have to be made on electrified tracks, and while repairs are being made on others from which the voltage has been removed. The value of placing the distribution system in the hands of the signal operators may be again illustrated by saying that should an electric train run past a stop-signal set by the operator, or should the operator desire to stop a train in his block he has only to trip the pilot-switch controlling the trolley circuit-breaker, from which the train is drawing its power, and signal the operator in the adjacent tower to do likewise. The individual value of this protective perquisite is an illustration of the use of sectionalizing outside of the question of line troubles.

As before stated, it is impossible to elect some standard distance for sectionalizing the line and then apply it to a steam road undergoing electrification. It is possible to conceive of an entirely new electric line subjected to this hypothetical course of procedure, but even in this extreme case it is difficult to escape the exceptions that could be taken to it; for example, what a strange coincidence it would be to find fifty towns just two miles apart along a railroad's right-of-way. On the other hand, how important each town would be whereat to locate a signal tower with its complement of electrical equipment.

In the discussion of sectionalization it would seem proper, therefore, that instead of specifying the length of sections, to specify the number to be used over a given total distance; their individual length varying in accordance with the local conditions peculiarly related to them. Upon this basis, it will be interesting to enumerate the following advantages and disadvantages peculiar to a choice of a "small number" and a "large number" of sections over a given distance. In this table it should be remembered that usually the items of advantage for the "small number" of sections will be items of disadvantage for the "larger number" and vice-versa. Also it is assumed that the signal towers along the right-of-way average

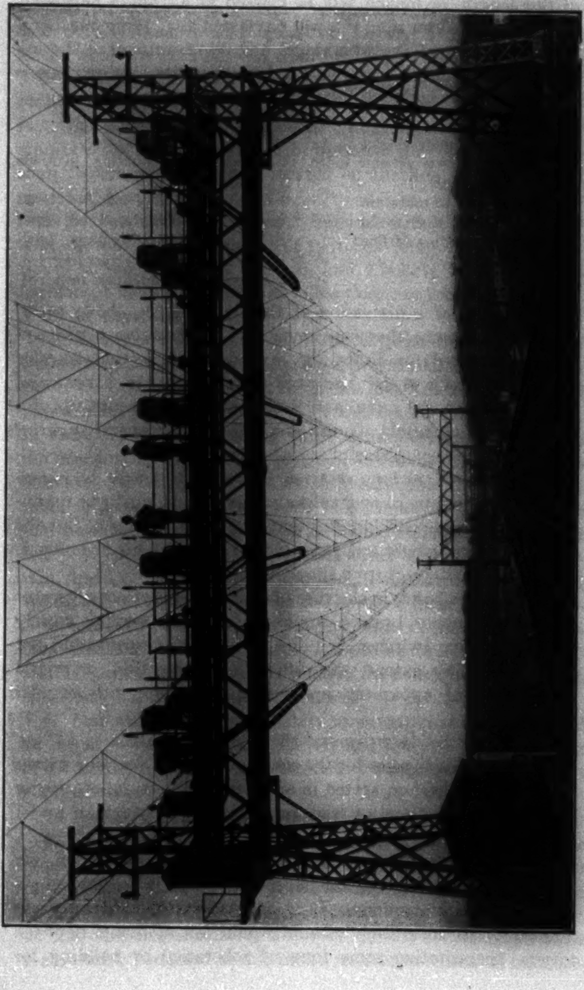


FIG. 3

about one and a-half miles apart and that electrical sections of this length, or longer, will be classed as a " small number " and sections shorter than this will be classed as a "large number."

A tabulation of the advantages and disadvantages of the use of a " small number " against a " large number " of sections is as follows:

Small Number

| *Advantages* | *Disadvantages* |
|---|---|
| 1 Co-terminus tower scheme more easily arranged. | 1 Difficulty of locating grounds increased |
| 2 Less switches to maintain. | 2 Greater section of track cut dead in case of ground or other trouble. Disadvantage, however, related to cross-overs. |
| 3 More reliable; due to less frequent grounding of line. | 3 Larger section breakers required |
| 4 Less cost. | |

In advance of a discussion of the items in the above table it is fair to assume that convenience of construction of the apparatus required for either the long or short sections may be equated. That is to say, the work-train service, in either case, would be about the same, and the structures to be put up of a character which would require much the same general superintendence and engineering.

In the case of the long sections, it would, of course, be necessary to splice the messenger cables, as they could hardly be manufactured on single reels greater than two miles in length, but the splicing process would not be a matter of great inconvenience, and would not detract from the value of the cables.

On the other hand, in the case of the shorter sections a greater number of anchor bridges would be required for the supply of sectionalizing switches, but this form of structure would not increase, to any extent, the difficulties of erection, or would the placing of apparatus upon them interfere with regular traffic.

Taking up the discussion of the above tabulation of advantages and disadvantages for the small number of sections versus the larger number; or, stated in another way, sections of greater length versus sections of shorter length, we note that under " advantages."

1. *Co-terminus tower scheme more easily arranged.* In my estimation this is by far the most important factor favoring a small number of sections. It is quite clear that with a great number of sections, their termini would fall at points between towers, necessitating some form of substation or building for

the electrical operators. This would be inconvenient, both for the railroad company and the operator, on account of the cost of maintenance and operation for the former, while the latter would be far removed from his living point.

The reason that the co-terminus scheme is more readily arranged with the use of long sections is apparent, in view of the fact that no convention is necessary to be followed in regard to standard distances, it being at the option of the engineer to choose such towers as are already located on the line as a termini of electrical blocks.

2. *Less switches to maintain.* This advantage is immediately seen, in view of the number of switches being directly proportional to the number of sections, and I believe there is general agreement that a switch in any line does not increase the reliability of that line.

3. *More reliable, due to less frequent grounding of line.* At the present stage of the art, the anchor insulators, which have given the best results from a combined mechanical and electrical strain point of view, have been of corrugated cylindrical form. In this form their insulating value is unquestionably less than the mushroom or petticoat type of insulator, and experience indicates that they are very much less reliable than the mushroom or petticoat type (this form of insulator is used to support the messenger cables on intermediate catenary bridges). It is my belief, however, that by suspending some form of protective shield or petticoat from the anchor insulator, its insulating value will be greatly enhanced. The blast from steam locomotives seems to produce a very rough enamel of coal dust and cinders, which, on account of deeply imbedding itself in the insulator, is almost impossible to remove, in consequence of which insulating values are greatly reduced.

4. *Less cost.* It is immediately apparent that the cost would be much less on account of the elimination of a larger amount of switching apparatus and the heavy bridge work required at all anchorages.

In the table of "Disadvantages" we note:

1. *Difficulty of locating grounds increased.* This is quite apparent, in view of the fact that there are a greater number of insulators between the circuit-breakers, but experience in actual operation has indicated that this is not a serious matter, as the offending insulators are very quickly located, and there is also being perfected at this time a resistance scheme of measure-

ment by which the point of ground can be approximated within 5 % of its actual location; and upon the perfection of this apparatus this difficulty will be eliminated.

2. *Greater section of track cut dead in case of ground or other trouble; disadvantage, however, related to cross-overs.* This trouble would be of a more serious character if it were railroad practice to include a great many cross-overs on the main line. The average distance between cross-overs on the New Haven road is even greater than the distance of the electrical blocks; in consequence of this, should a section become dead on account of a ground, it is possible that the train would have to cross over at a distance from the trouble greater than the length of the electrical section. Railroad engineers look upon cross-overs as a necessary evil (remembering their high cost of maintenance, together with the necessity of interlocking machines in conjunction with them) and it is fair to assume that their distance apart will not be decreased for the convenience of shortening the electrical sections; hence, this difficulty cannot be classed as one of special moment.

3. *Larger section breakers required.* In the use of longer sections, it is apparent that more trains may be drawing power from the section breakers, in consequence of which it is necessary to design them for greater capacity and they will be called upon to open larger propulsion currents. The difficulty of this, however, fades in the maximum demand upon the breakers being a short circuit, and as this is a duty a section breaker of any capacity has to stand ready to perform, this objection might be considered as not existing.

It would be a strange state of affairs if it were impossible to improve upon any principle or form of construction adopted. In regard to principles which have governed in the electrification and sectionalization as adopted by the New Haven road, I have found by careful inquiry into the opinion of those who are responsible for the operation of our electric trains and the distribution of currents to them, that if any change were to be made, possibly some advantages would accrue in the use of a longer section.

In regard to form of construction. It is fair to say that there are many changes that can be and are being made, which will greatly increase the efficacy of distribution. It is my observation that the New Haven electrification has been looked upon as a radical departure from engineering practice. There is no question about the justice of such a remark when viewing the matter as a whole. If, however, we segregate each link in the chain which forms the whole, I believe it will be found that no one link is a particular departure from a practice that has existed many years. It has simply been the putting together of old principles into a new form. One exception can be made to this statement. The alternating-current railway motor is new, and yet an exposition of its characteristics, such as in its speed and torque curves, show that within it the old underlying principles prevail. Its complements, the power-house and line, involve no new principles that have not been tried out under various forms and conditions. A high-tension moving contact has nothing new or of a disturbing nature about it.

When the form of electrification of the New York division came up for decision, there was an easy path of the least resistance open to the engineers of the New Haven road. A form of electrification had been adopted and applied to traffic rails over which the New Haven trains were obliged to go in their entrance to New York City. An acceptance of this form of electrification would have simplified and made easy the duties and responsibility of the engineers of the New Haven road. The right path, however, is not always the easiest, and the principles which existed in their minds were of a character that required a radical departure from the easy and tempting alternative. There is an old saying: "Nothing that is worth while ever came easy," and such has been the case with the New Haven road. We have encountered unexpected difficulties, which are always common to initiative, none of them, however, has been of a character which could be interpreted as a menace to the general principles involved. The difficulties have either been corrected or their correction is easily in sight.

The last six months of operation have offered the opportunity for a collection of valuable data, and the following observations and recommendations are offered in the hope that they may be of some value to other engineers interested in the electrification of steam roads:

1. In one-, two-, three-, or four-track railroads, the single-phase distribution should include besides the trolley wires, by-passes or feeders.

2. Electrical sections should not average less than 1.5 miles in length; greater averages are entirely acceptable and individual lengths should be governed by local conditions.

3. Twenty-two feet is a safe general working distance of trolley from rail.

4. The de-insulating effect of steam locomotives stack discharges is a most important consideration to be kept in mind in the matter of properly insulating high-tension wires from ground.

5. High insulation factors should be used where high-tension construction due to low bridges is brought nearer the rails than the normal height of 22 feet. Strong mechanical shields should be used to deflect locomotive blasts from messenger insulators at low bridges. Care should be exercised in the installation of these shields so that high-tension conductors and ground are at safe working distance. Wherever possible insulators should be installed away from the direct line of the locomotive blast.

6. Auxiliary wires in connection with the electrification, if they cannot be carried over highway bridges as aerial conductors, should not be carried under, unless they are enclosed in lead-covered cables, with end-bells properly enclosed in suitable housings at points where the conductors change from aerial to lead-covered cables.

7. All circuit-breakers connecting feed wires (or by-passes) to the trolley bus-bars should be equipped with time-relays, so that any short-circuit will immediately open the trolley-breakers, thus locating the trolley section grounded. Equipping the feeder breakers with time-relays insures continuity of voltage on wires not affected by the short-circuit. Each trolley-breaker pilot-switch should be provided with a light to indicate when it opens, and an announcer bell should ring in the signal tower at the same time so that the operator is promptly notified.

8. On account of deleterious influences of weather and locomotive stack discharges, together with general inconvenience of getting at bus-bars and switches when installed on anchor bridges, all section oil-switches should be installed in switch houses erected at the side of the tracks, with lead-covered cable connections between trolley and switches.

9. Signaling should be arranged so that the operator can prevent the engineer from spanning two sections by his locomotive shoes in the event of the advance section being grounded.

10. All signal towers should be interconnected with a reliable telephone service. Immunity from electromagnetic and electrostatic disturbance in the telephone system can be secured by

using twisted-wire pairs enclosed in lead-covered sheath, the sheath being grounded frequently. This suggestion is more particularly applicable to the interrupted or tower-to-tower telephone system. In this case the distance of exposures of the telephone wires is not great, and thus the summated effect of electromagnetic induction is negligible. In the case of the through telephone line where the circuit is uninterrupted throughout the zone of electrification, again the lead sheath and twisted pair are respectively effective in removing all static charges, and electromagnetically balancing the circuit; but on account of the cumulative action of the electromagnetic induction, either compensating transformers or a system of impedance coils installed across the telephone circuits at intervals of two miles (this distance may be less, depending on the electromagnetic density) with their central points grounded should be used. Either method will satisfactorily remove the impressed voltage due to electromagnetic induction. The importance of reliable telephone service between operating towers cannot be too greatly emphasized.

The above mentioned are some of the fundamental requisites which design and practice have brought out in connection with the New Haven electrification. Design and practice are many times good friends, but if a difference of opinion arises, practice will, in nine times out of ten, have the better of the argument. Experience, the great teacher, has brought out either the efficacy of the original design or the proper modification of it.

The observations and recommendations above cited, are those that have been impressed upon the writer during the period of operation so far attained. Except for certain minor and easily remedied details, experience to date with the New Haven arrangement of single-phase distribution would indicate that the fundamental principles involved have been correctly applied.

## DISCUSSION ON "THE NEW HAVEN SYSTEM OF SINGLE-PHASE DISTRIBUTION, WITH SPECIAL REFERENCE TO SECTIONALIZATION." NEW YORK, JANUARY 10, 1908.

**W. S. Murray:** A retrospect always reveals more than a forecast. A perusal of the paper indicates to me, as doubtless to you all, that what has been touched upon is only a small percentage of the interesting and valuable data that could have been included were it at the election of the author to give his undivided attention to the subject.

I shall not attempt to apologize for what the paper lacks, and can simply say that odd moments, particularly those occurring while riding on the trains of the railroad company, supplied the time during which the article was written.

There has been no attempt to go into either the electrical or mechanical specifications of the distribution system. These were all included in the several contracts existing between the railroad company and the manufacturers and contractors, the general outline of which covers all points bearing upon the physical performance of the material furnished. As far as it was possible to anticipate, various weather conditions were considered in the design of all parts subject to changes of temperature, to wind, and to ice formation. We have passed through several snow, ice, and wind storms, and combinations of these, and all the iron structures, messenger, trolley, and feeder wires, have satisfactorily demonstrated the factors of safety which were included in their design.

A description of the electrical and mechanical details of the distributing system of the New Haven road has appeared in the columns of the engineering papers. My aim to-night has been more to acquaint you with some of our experiences rather than our theories. Therefore, fully conscious of many glittering omissions germane to the subject, and counting on the discussion to bring them out, I shall read the paper. [Here Mr. Murray read his paper.]

The discussion of double or single catenary construction on main-line electrification was intentionally omitted from the paper. A choice of the one or the other must be a compromise of a great many considerations, the principal ones being the number of tracks to be electrified, and local conditions; but there is one fact that has been conclusively demonstrated to me, namely, either the trolley wire or the trolley shoe must be flexible, whether the construction be for main or for branch lines. Of course in the single catenary construction a flexible contact conductor is provided. In the triangular construction, the contact conductor is rigid. This requires a flexible shoe, which in a degree is secured by the spring pantagraph arrangement. Experience, however, has forced upon me the conclusion that the pantagraph must be still further supplemented by a light but strong mechanism which will insure flexible contact between the shoe and trolley wire, thus not offering a great deal of inertia in movement when the shoe meets the hard spots of the line which exists at the catenary hanger points.

A form of construction we have adopted in our East Port-Chester yard, in which the latitudinal catenaries are supported by cross-catenaries—in some cases spanning as many as ten tracks—has about it a great many attractive features, and I am not too sure that experience will not bring out the possibility of using the cross-catenary for main line work. Such an arrangement, if more frequently reinforced with cross-bridge anchorages such as now used in the New Haven electrification, will bring a lighter and cheaper construction, and possibly afford a greater opportunity in insulating the overhead system from ground. I can see no reason why single catenary spans need be made any less than those used in the double catenary construction, as the cross-rigidity that may be desired can be obtained by tying into adjacent latitudinal catenaries, all of which, of course, are subject to the pull-off construction at present employed. Of course there are a great many pros and cons about this, and again we are forced to the conclusion that to-day is not the time for standardization, as it will pay not to accelerate our conclusions at a greater rate than the operating evidence upon which they should be based.

Still another point that has not been touched upon in the paper, is the great flexibility offered in the double-switch arrangement of supplying power to a trolley wire at the two extremities of its section. It is readily seen that if trouble exists in one of the circuit-breakers supplying a trolley wire in any given section, this switch can be immediately cut out and all the power supplied from the remaining switch at the other end. This flexibility, of course, is secured in virtue of the low loss due to high-tension transmission, and the employment of by-passes or feeders, to which previous reference has been made.

An impression has come to me that I might have dwelt more fully on the details of the system of distribution. As stated previously, it has been so universally described in the engineering papers that I have felt as if I were writing about results and experiences with something the general parts of which we were all acquainted. If I have universal support in this impression, I can only offer in amelioration, Diagram (4), which assembles all the links of our transmission chain, the functions of any one link of which are common knowledge.

**L. B. Stillwell:** I have not found time to read Mr. Murray's paper carefully, and I do not propose to criticize the sectionalization of the New Haven and Hartford trolley or its feeder layout. I have a very high opinion of the importance of these parts of the plant, which unquestionably are too often neglected. There are cases where very large investments have been made to insure continuity of service in which, judging by results, the investment has not been made in the right place. Instances might be mentioned in which, at great expense, excess generating capacity has been installed adequate to take care of the service, even in case of destruction of 50 per cent. of the total generating plant, and yet when the feeder layout was under consideration oversights apparently have occurred as the result of which very severe interruptions of service have followed. Unquestionably, therefore, criticism of the organization of supply circuits for large distributing plants, particularly for railway service, is highly beneficial. I say particularly in railway service, because in industrial power service the interruption of a feeder now ordinarily involves only a local and a very temporary failure of service; whereas in railway operation if we stop trains on one part of the line we are liable to hold up the entire operation of the railway.

**W. B. Potter:** The ordinary 600-volt trolley line is of little value as a standard with which to compare the 11,000-volt catenary under steam railroad conditions. Considered as an example of good construction, I have never seen the equal of the catenary to which Mr. Murray refers. As to the relative reliability and maintenance of such an overhead high-voltage trolley compared with a 600-volt third-rail, under conditions necessitating joint operation with steam, I believe this to be a debatable question.

I agree with Mr. Murray as to the desirability of a through feeder in parallel with the different sections; I do not see the need, however, of two such feeders on the same phase as the trolley wires. For local power the combination of the single feeder with the trolley wires would seem sufficient reserve. If any accident involved all four of the trolley wires, it would probably include the feeder as well; in case it did not, a single feeder could supply power beyond the break.

As to the length of the main-line sections, I favor from three to five miles, rather than less; as this question affects the reliability of operation, it seems that a reduction in the number of switching appliances would be favorable. Five-mile sections have proved satisfactory in third-rail operation, and there appears to be no reason for shorter sections with the high-voltage trolley, unless it is the greater liability of the longer sections to break down. It seems desirable, however, that at track cross-overs there should be a short section controlling the main-line and cross-over tracks, the better to insure cross-over movements in the event of interruption on the main-line sections.

Twenty-two feet seems to be a generally recognized standard height of trolley wire. It is unfortunate that this height cannot be maintained throughout, as it would then be possible to use a much lighter form of pantagraph. Overhead bridges, with their limited clearances, often necessitate a vertical movement of the collector of from seven to eight feet, and this condition requires a pantagraph structure more liable to derangement.

Depreciation of the catenary insulation from steam locomotive smoke would naturally be expected, and the extent of trouble from this cause seems to have a bearing on the permissible trolley voltage. Conditions might well arise where either copper or efficiency would have to be sacrificed for reliability.

The suggestions with regard to time-relays and switch indication are in line with well established practice. As to the method of operating the circuit-breakers, I understand that they are at present controlled from the main power circuit. Should not some means be provided for operating these switches in the event of failure of power? As these circuit-breakers are near signal towers, where manual operation could be conveniently applied, would not this be the more reliable method? Lever connections would provide certainty of operation and would not interfere with the automatic tripping. The proposed change from the bridges to switch houses would simplify the mechanical connections.

There is no doubt as to the desirability of guarding against the spanning of two trolley sections, as there is always the possibility of one section being grounded. Such accidents will occur. If the two pantagraphs or trolleys are far enough apart to span the section insulators, the only safeguard seems to be a fuse located between the two collectors.

**O. S. Lyford, Jr.:** Mr Murray's paper is written from the point of view of operation of a multiple-track road: when viewed from the standpoint of single-track operation, this subject has some rather different aspects. For instance, Mr. Murray says:

> 1. In one-, two-, three-, or four-track railroads, the single-phase distribution should include, besides the trolley wires, by-passes or feeders.

I do not take exception to this statement as relating to two-, three-, or four-track roads, but it does not necessarily apply to single-track roads. The objects of sectionalization are three: first, to minimize the interference with the operation of the road in case of line trouble; secondly, to locate the fault quickly; and thirdly, to reach the fault with a work train.

As to the first object, to minimize the interference with operation, I think it is quite apparent that a parallel feeder is not of much use as a by-pass in a single-track road of moderate length. Take, for illustration, the Erie road south from Rochester, Fig. 1. This is a single-track road, running from Rochester to Mount Morris. Power from Niagara Falls is received at a sub-station at Avon. At present the lines north and south from Avon are operated as two legs of a three-phase system, the common point being connected to the track. Avon is a junction-point with an east and west line of the same road. Rochester is about nineteen miles from Avon, and Avon is about fifteen miles from Mt. Morris. With a schedule speed of about twenty-four miles an hour and hourly service in each direction, it is apparent that a dead point anywhere on the line will, in a few minutes, block all trains on one side of the junction. The ability to move trains up to the dead point will not materially help the service.

The Erie line is divided into sections, but the principal object of sectionalization is to locate the fault quickly. The section breakers are "jumpered" through hand-operated switches and are placed near passenger stations or signal towers. If there is trouble, the system operator, by telephone orders, can have the section switches opened in sequence and quickly locate the section on which the trouble occurs. Mr. Murray speaks of special apparatus being developed to test for faults and locate them quickly. If such apparatus be produced, it will probably be more convenient than the use of section switches.

Considering the third object—to reach the fault with a work train—even with short sections such as have been discussed to-night, the work train, if operated by trolley, could not get within three-quarters of a mile or so of the fault, and it would be impracticable for the men to have to go the rest of the way on foot to make the repairs. The logical conclusion, therefore, is that the work train should be operated by an independent unit, either a steam locomotive or a gasolene car, preferably the latter, because it is more easily put in service.

Independent operation of long sections between important points is desirable. Usually, however, this will be best accomplished by high-tension feeders, rather than by by-pass feeders operated at the trolley voltage. The Erie system has been planned so that if the electrification is extended beyond the limit for economical transmission at 11,000 volts (for instance from Mt. Morris to Dansville) the present transformers may be connected so as to obtain either 11,000 or 22,000 volts, and 22,000-volt feeders may be carried to the distant section, serving the trolley wire through autotransformers. This plan allows transmission at double voltage and saves copper without appreciable complication.

Another case may serve to illustrate the conditions which arise in single-phase operation. The Denver & Interurban Railroad line from Denver to Boulder has a single-track main line and two single-track branches (see Fig. 2.) The power house is about 2 miles from the Louisville branch and 5.2 miles from the junction point. Power is supplied over two feeders from 11,000-volt, single-phase generators to the junction point. The length of the Marshall branch is 12.8 miles, Louisville branch 12 miles, and the Denver line 15.2 miles.

In this case it is obvious that there will be material advantage gained by being able to operate each branch independently, and provision has been made accordingly; but by-pass feeders for each branch would not help matters much in case of line trouble. The trolley wire, in this case, as with the Erie, has been provided with section breakers placed about 4 miles apart for convenience in locating faults.

There are other things to be taken into account besides the actual line trouble; that is to say, the problem is not merely to locate and repair the fault. On any railroad provided with

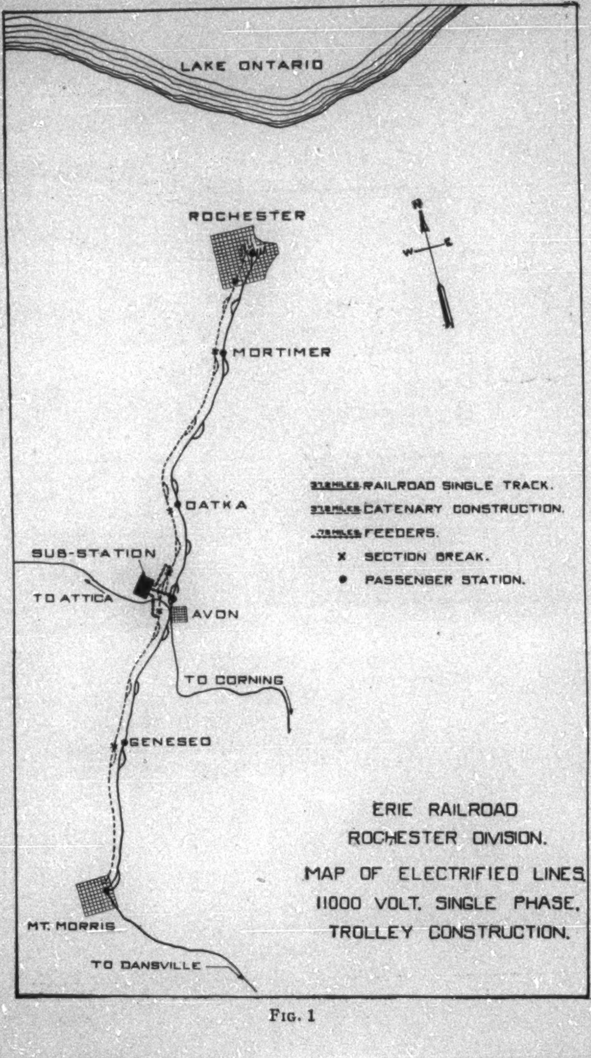

LAKE ONTARIO
ROCHESTER
N
W
E
MORTIMER
37.2 MILES RAILROAD SINGLE TRACK.
37.2 MILES CATENARY CONSTRUCTION.
7.5 MILES FEEDERS.
× SECTION BREAK.
● PASSENGER STATION.
OATKA
SUB-STATION
TO ATTICA
AVON
TO CORNING
GENESEO
ERIE RAILROAD
ROCHESTER DIVISION.
MAP OF ELECTRIFIED LINES
11000 VOLT. SINGLE PHASE.
TROLLEY CONSTRUCTION.
MT. MORRIS
TO DANSVILLE

FIG. 1

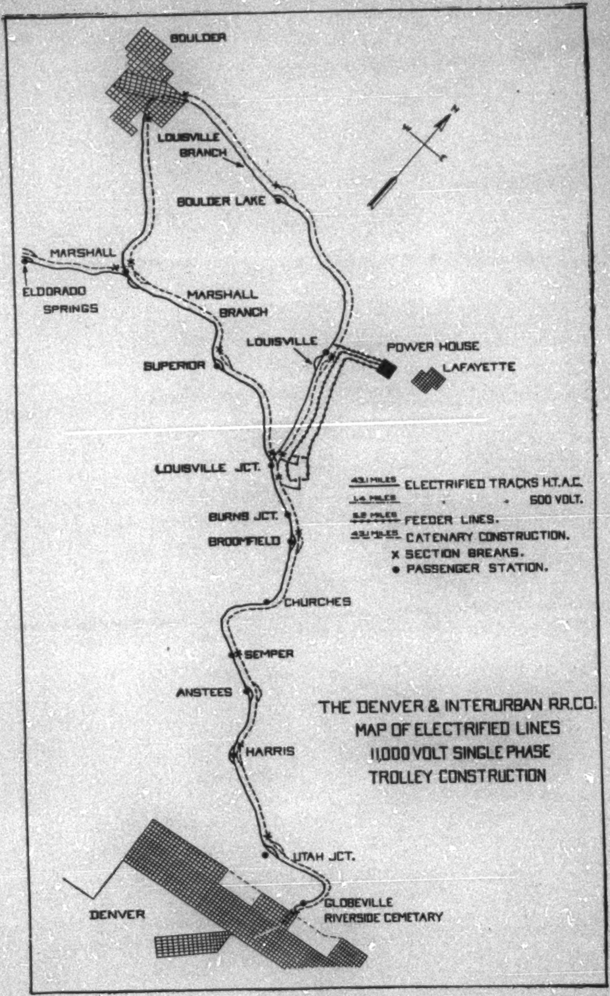

BOULDER
LOUISVILLE BRANCH
BOULDER LAKE
MARSHALL
ELDORADO SPRINGS
MARSHALL BRANCH
LOUISVILLE
POWER HOUSE
LAFAYETTE
SUPERIOR
LOUISVILLE JCT.
43.1 MILES ELECTRIFIED TRACKS H.T.A.C.
1.4 MILES " " 600 VOLT.
5.8 MILES FEEDER LINES.
43.1 MILES CATENARY CONSTRUCTION.
X SECTION BREAKS.
● PASSENGER STATION.
BURNS JCT.
BROOMFIELD
CHURCHES
SEMPER
ANSTEES
HARRIS
THE DENVER & INTERURBAN RR.CO.
MAP OF ELECTRIFIED LINES
11,000 VOLT SINGLE PHASE
TROLLEY CONSTRUCTION
UTAH JCT.
GLOBEVILLE
RIVERSIDE CEMETARY
DENVER

FIG. 2

a positive block system, the process of having the rules set aside so that a "special" can proceed against the block is about as difficult as to repair the fault itself. Most of the time of a service interruption is consumed in reaching the fault, not in locating or repairing it. Sectionalization does not help this part of the problem.

The natural answer to all of this is that the high-voltage trolley system must be put up so that line troubles rarely occur. That looks like quite a task with 11,000-volt operation, but as one gets acquainted with this high voltage construction most of the difficulties disappear. One important feature, according to present practice, is the exclusive use of porcelain for insulation. At first it looked as if the porcelain could not safely be subjected to the heavy physical strains of the catenary construction, but it has been found that standard forms of insulators, when properly harnessed, can be tested out with 14,000 lb. compression and 22,000 volts electrical strain at the same time. Thus far the physical strains in the catenary circuits do not exceed 5,000 lb. per wire, and there will be a factor of safety of about three for an insulator in a single wire or half that, if one insulator is used for both messenger and trolley wires. The use of built-up insulators is not promising. The use of wood, although the wood may be a good insulator, has the objection that if there be leakage across the wood and the wood be burned in two, then down comes the catenary construction. With porcelain properly harnessed, the only result of a broken insulator is reduced insulation. The line does not come down, because the harness is interlocked. With two insulators in tandem, the line will remain operative.

Mr. Murray's third recommendation of 22 ft. for general working distance of the trolley from the rail, seems to be about right, as has been said once or twice this evening, and this means a standard clearance of 24 ft. above the rail for the "through" and "under" bridges, and still greater clearances for other overhead structures, whenever physical conditions permit. In a large majority of cases (barring tunnels and city street-crossings) new construction can be designed for 24 ft. clearance without much difficulty or material effect in cost. The troubles of the electrical engineer will be materially reduced if the railways will make this the standard clearance for new construction.

The feature of high insulation factors for construction under low bridges should be characteristic throughout the entire installation, for the reasons which I have given. There is no reason for not having such an insulation factor.

Mr. Murray also speaks of the auxiliary wires passing under bridges, and advises the use of lead-covered cables with end-bells. A short section of insulated cable, in a grounded sheath, in the middle of a long overhead line, is a mighty difficult thing to install properly so that the insulation will not be frequently broken down. Inasmuch as the trolley wire has to go under the bridge, and the trolley must be bare, it would seem possible to put the auxiliary wire under the bridge in much the same way, and with equal safety.

One gratifying feature about catenary construction erected on grounded brackets or grounded bridges is that there are grounded structures close to and frequently above the live wires, and consequently little probability of disturbance from lightning. The Rochester division of the Erie road has been in operation for about eight months, and through nearly all the lightning season of last year there was practically no disturbance on the 11,000-volt system due to lightning, although there were bad thunder storms through that district, and a nearby high-tension line was struck repeatedly. On the other hand, in the single-phase system there occur occasionally heavy disturbances resulting in surges approximating lightning in severity, and if anything but porcelain be used for insulation (for instance, in the case of lead-covered cables above referred to) I should anticipate that such surges would occasionally break through the insulation.

On this Rochester division there is a telephone system on the same poles with the trolley line. With proper transpositions and suitable means for removing the "static" from the telephone line, it operates satisfactorily and without shock to the operators.

**W. S. Murray:** I am happy to feel that Mr. Stillwell bears me out along the ideas of a practical investigation. I think that mental reservations on this floor, where our mistakes may be brought out and discussed, is a great error. Our mistakes teach us more than our theories, and I think this floor is the place to discuss our troubles as well as our successes.

Mr. Potter spoke of pinning his faith to the third-rail instead of the overhead construction. In regard to that, I can simply say this is a problem much larger than the one we are discussing to-night; but I have reason to believe that on long-distance traction work the question of operating expense will unquestionably be the paramount feature, and hold the overhead construction and alternating-current transmission direct to motors a necessity. I can almost say that experience bears me out in this regard, even within restricted zones of electric traction.

I think that the necessity of two feeders can be explained quickly by saying that in the event of trouble the interlocking of the feeder system as established on the New Haven road is such that if trouble occurs on one feeder, by by-passing around through switches on the anchor bridges we are enabled to cut out any feeder-section and make repairs, thereby giving a more reliable continuity of service.

I thoroughly agree with Mr. Potter that the sections should be greater in length. I think that from three to five miles sounds reasonable, but local conditions govern better what the actual distance should be. I am quite convinced that were we to draw up specifications for the New Haven electrification again, I would be in favor of a longer section. This, as brought out in the paper, does not interfere with the conterminous arrangement of towers, which is most important.

In regard to pantagraphs operating under low bridges, Mr. Potter has brought out an important and deleterious feature of the overhead system. It is a problem that must be solved. We first started our electrification by a system of supports under low bridges, at very short intervals, and the result was, due to the effect of the locomotive blasts, that grounds developed very rapidly. This trouble has been overcome by eliminating the large number of supports, resorting to only two; and, instead of having the insulation in the middle point directly over the track, as at first installed, it has been placed at the side, so that the locomotive blasts do not affect the main insulators. Since we changed the construction to the latter arrangement, we have experienced absolutely no trouble in the grounding of the contact conductor (or messenger cables which are connected to it) under low bridges. This form of construction has been in use for four or five months.

In regard to the fact that for mechanical reasons we have to increase the copper in overhead construction high-tension work, the fact also must not be overlooked that the total copper is still in a minute ratio to the amount of copper required for an equivalent amount of power with the same loss transmitted on the alternating-current—direct-current system.

Operating the anchor bridge switches by levers would bring an increase of operating cost. I do not approve of this, particularly as lever arrangements in switches have been abandoned as cumbersome in places where quick action is required, and such a place as the operating towers calls for quick action.

In general, I agree with Mr. Lyford about the single-track feeder arrangement. In its application to long distances, however, I think a feeder arrangement for single-track construction is quite necessary, particularly where the headway is short and the traffic heavy. Should such trouble as he spoke of develop in the middle of the line, it is not uncommon in railway practice to operate to that point on both sides. In such a contingency the feeder or by-pass offers quick relief; it is not costly, and is constantly saving power. I certainly agree with him in regard to porcelain insulation in the place of moulded material, if it is possible to obtain the tension and compression strains in porcelain that is obtained in molded material.

Mr. Lyford's suggestion to use the same form of feeder construction under low bridges as is adopted in the trolley is a good one, provided the clearances can be obtained under the low bridges in question. Abutment walls are so near to the tracks that it becomes a rather difficult thing to put in this kind of construction, especially if, besides feeders, other wires, such as power wires and signal wires, have to be taken care of.

*A paper presented at a special meeting of the American Institute of Electrical Engineers, New York, January 24, 1908.*

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# THE BEST ENGINEERING EDUCATION

## An introduction to a digest of the papers on engineering education in the Transactions of the American Institute of Electrical Engineers, with a view to renewed discussion of the points contained therein

BY CHAS. F. SCOTT

The recent rapid development of the electrical industry owes its vitality to the engineering school. Its graduates have done the designing, constructing, operating, and directing which have made possible the rapid progress and wide extension in the use of electricity. The ideals, the equipment, and the methods in engineering education, as well as the number and size of the schools, show a remarkable rate of progress. In fact, the advance in the electrical industry, in engineering education, and in the American Institute of Electrical Engineers closely correspond when measured numerically. There has been a close interrelation between them.

The future prosperity of the industry and of the Institute depends upon the efficiency of engineering education to an extent which one realizes more fully the closer he studies the subject. It well merits our best thought.

A review of the papers which have been presented to the Institute on engineering education shows that among our modern professors there are those who are active and alert and up-to-date. There is a marked agreement between the teaching profession and the engineering profession, both in an appreciation of the importance of the subject and in the general purposes which the engineering school should aim to accomplish. As engineers, it is quite unnecessary to argue that our schools should be more efficient and that their graduates should be better equipped for the work they are to do, as the professors are urging us to tell them how to accomplish these very objects.

Before discussing how to do something, it would be well to decide what it is we desire to do. What do those who use engineering graduates want them to be able to do? Ideas have varied. Some expect trained artisans, others, trained engineers who are ready at once to do any kind of engineering work. Some expect technical specialists; while others call for men of ability who have a general preparedness for doing any kind of work. Some are disappointed if graduates are not immediately productive; while others provide courses of practical training. As all boys are not alike, and as their future employers have different ideas, and as their jobs will not be the same, it reasonably follows that there is room for more than one kind of training in college. The problem is not wholly abstract; it is vitally concrete. Its solution is not a rigid and narrow one, but it involves general policies. The details of method are to be determined by varying conditions and are to be adapted to the varying personal qualities of the young men.

In general, instruction in engineering schools is of three varieties:

*a.* Practical or industrial.
*b.* Scientific.
*c.* Cultural.

Practical or industrial studies are intended either as illustrations of scientific principles or as a direct preparation for business or professional life.

Scientific studies are the foundation for the applications and make the latter possible.

Cultural studies broaden the student's mental horizon, offset the narrowing effects of technical studies, and prepare for activities which are not purely technical.

The best engineering education is that which fits the individual student for his largest development and usefulness ***in the long run***, not necessarily immediately after graduation. The problem, therefore, is to divide the four years spent in school among the three classes of studies in such proportion as will bring about the best results.

The problem is largely one of elimination, as, if all the studies were included which have been suggested as being essential or desirable in the training of an engineering student, the college period of 4 years would have to be increased to possibly 20 or 30 years.

Among the questions which arise in the discussion are the following:

1. The desirable characteristics of the acceptable graduate with respect to:

*a*. Practical familiarity with electrical apparatus which will enable him to be immediately useful, versus a less practical and more general training, which is to be supplemented by an apprenticeship course or its equivalent.

*b*. Specialized technical training and technical knowledge, versus a broader education aimed to develop intellectual power rather than the acquisition of technical knowledge.

2. The arrangement of subjects and courses which will best produce the desired results. The following questions arise:

*a*. The relative attention to be given to the practical or industrial, the scientific, and the cultural.

*b*. The relative proportion between subjects which are valuable for imparting technical knowledge and those affording training in scientific and logical methods.

*c*. The relation between school instruction and practical work; whether one should precede the other, and if so which one should come first, or whether they should alternate once a day, once a year, or at some other rate.

*d*. The importance of current engineering practice; of lectures by practising engineers; of discussion of current topics in local meetings of the Institute.

*e*. The degree of desirable differentiation in courses or methods on account of differences in the characteristics of individual students or in the fields of work they expect to enter.

*f*. The sequence of subjects—whether the theroetical groundwork should be laid during the first few years and the practical subjects reserved until the latter part of the course, or whether an intermingling of the two in accordance with the concentric method outlined by Professor Karapetoff is to be preferred.

I venture the prediction that the solution which will find most general acceptance will be that which gives to each student the training which fits him for his largest individual development; that for those who are qualified to take an active rather than a passive attitude toward their work the broader education, which emphasizes training rather than knowledge, will be chosen; that a fairly intimate intermingling of college work with practical work will be found to conduce to the efficiency of each, and that the field in which the greatest difference of opinion will be present will be with regard to the proposed concentric method. This system clashes with time-honored educational ideals, but it presents arguments which are so rational that the existing method must assume the defensive.

Those who were present at the Niagara convention will recall that the discussion on the papers of Professors Norris and Karapetoff was one of the most animated during the convention, and that it was brought to a close only on account of lack of time, although it had continued for nearly an hour after the ordinary hour for adjournment. It was the interest in this discussion which led to the appointment of an Educational Committee by the Institute, and which has led to the present summary (prepared by Professor Norris, chairman of the Educational Committee) of the educational papers in our TRANSACTIONS as a basis for the active continued discussion of this important subject.

## DIGEST OF INSTITUTE PAPERS ON EDUCATION

### 1892. ANNUAL CONVENTION, CHICAGO

**Robert B. Owens.** The first formal paper on engineering education was presented by Professor Owens under the title, "Electrotechnical Education". The value of the manual element is emphasized and attention is called to the departments of mechanic arts which had been attached to the Massachusetts Institute of Technology, the Washington University, and others. A technical school [according to the author] is primarily a place for the preparation of men who expect to earn their living as engineers. It is not a school of general culture nor is it a school of exact science. It is a device to save time, and teaches the application of pure science to industrial purposes. It is also a post-graduate school, and in this respect should rank with schools of law and medicine. Professor Owens at that time advocated the employment of a number of specialists in order that each student might have the opportunity to choose the work for which he is best fitted. While it is expensive to supply such specialists, and the equipment to enable them to carry on their work is costly, on the score of economy no more profitable expenditure of money is possible than for the support of technical schools. Education is not a money-making business, and can never be made to pay for itself.

Professor Owens outlines the elements of a course in technology, basing his recommendations upon the existence of three kinds of electrical engineers—"installing engineers, designing engineers, and engineering scientists".

**Dugald C. Jackson.** The technical education of the electrical engineer is one that should continue through life. Professor Jackson confines himself to a small part of this education, namely, the college education, and in order to be perfectly definite, he first outlines the course at the University of Wisconsin. The underlying principle is to depend on fundamental theories. with a common-sense view to their particular applications, in such a way as to aid in diagnosis, not by the application of a mathematical formula, but by comparing the accumulated experience of the practical world. It is comparatively easy to teach the fundamental theories, hence it is frequently overdone It is not so easy to educate the judgment of a student in electrical engineering, whose entire knowledge of his future profession is acquired from the electric bells in his father's house, and who may never have examined a dynamo, or storage-battery until he visited the college laboratory. Professor Jackson deplores the effect of the rigid specialization required in the technical school, and recommends a preparatory arts course when such is possible, and outlines the elements of the technical part of the course. It is interesting to note that in the paper delivered by him 11 years later he has not materially changed his views.

The discussion upon these two papers indicates the real interest taken in the subject at that early date.

### 1902. Annual Convention, Great Barrington

Between the years 1892 and 1902 practically no attention was paid to the subject of technical education.* In the latter year, a session of the annual convention was devoted to this subject.

**Chas. P. Steinmetz,** in his presidential address, called attention to the fact that all future progress in science and engineering depends upon the young generation, and to insure an unbroken advance it is of preeminent importance for the coming generation to enter the field properly fitted for the work. Here the outlook appears to him by no means entirely encouraging. The proper function of the educational institution is to give the student a thorough understanding of the fundamental principles of electrical engineering and allied sciences, and a good knowledge of the methods of dealing with engineering problems. At present the average college course does not do this. One of the reasons for the inefficiency of the college course is the competition between colleges, quantity having been increased at the expense of quality. Memory is developed at the expense of the reasoning faculty, and the college courses would be improved if one-half or more of the material taught should be dropped from their curricula, and the rest taught so as to be fully understood with reference to general principles and methods.

One objectionable feature of the instruction at most colleges is the "step-by-step" method. One subject is taken up, by application of sufficient time and energy pushed through, and then after the examination it is dropped and another subject is taken up. To understand a subject thoroughly requires several years' familiarity with it, so that the study of any subject which is not kept up during the whole college course might just as well be dropped altogether.

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* A. A. Hammerschlag prepared a paper in December 1898 on the subject of the education of electrical apprentices and foremen. This presented in an excellent manner the importance of properly training a class of men who could never be electrical engineers in the sense of their being technically trained. This paper is not abstracted here, as it is not in line with the general purpose of the resumé.

The present method of examination, which consists in expecting a student to answer ten questions or so in a few hours, is faulty. It shows what the student has memorized, but not how far he understands the subject. In electrical engineering, nothing beyond the general principles is needed for success; time spent in memorizing things to be forgotten afterwards is entirely wasted.

Dr. Steinmetz outlines the ideal course in electrical engineering, advising a good foundation in elementary mathematics, with no memorizing of integral formulas which can be looked up in a reference book when required. A thorough knowledge of science, including physics and chemistry, both theoretical and applied, is strongly urged. Electrical laboratory work should be taken up from the start, even before the theory is understood. Design of electrical apparatus is of secondary utility, and rather objectionable, with the exception of some very simple apparatus. Far better is the reverse operation, the analytical investigation of existing apparatus.

**Samuel Sheldon** called attention to the necessity for uniformity in electrical engineering courses, pointing out the wide difference in practice in various institutions; for example, engineering students at Cornell University spend ten times as much time on shopwork as those in the Massachusetts Institute of Technology. The range in the various subjects in terms of hour units* are in mathematics from 5 to 11; drawing, 3 to 10; physics and chemistry, 7 to 25; English, 0 to 11.3; French and German, 0 to 10; shopwork, 0 to 21; electrical engineering, 9.5 to 23.8; other engineering, 7.7 to 23.2; thesis and elective, 0 to 7.1. He points out that the aims of a liberal education are as follows:

1. To discipline the mind so as to create a power for coördinate thought.
2. To impart a knowledge of facts.
3. To develop a power of expression in language or in action.
4. To discipline emotional sympathy so as to develop an esthetic taste.
5. To discipline the moral faculty.

The curriculum has a twofold purpose. First to assist the student in choosing a calling which will be congenial and suited to his ability, and secondly to develop equally all his faculties. While radically different in purpose from the arts course, the technical course should produce something of the same results. On the other hand, the legitimate ultimate purposes of a technical institution are so utilitarian and different from those of the liberal institutions, that the extensive use of electives on the part of professors, which is so admirably adapted to ordinary college requirements, is detrimental to the best interests of the technical student and is wasteful of his time.

**William Esty.** At the same convention Professor Esty outlined several ways in which instruction can be made practical as well as scientific. The ideal education for the engineer is a literary and scientific course of a general nature, covering three or four years, followed by a special technical course extending from two to three additional years. The tendency to regard an engineering course as post-graduate professional work is increasing, as is evidenced by the increased number of graduates of humanistic colleges taking engineering studies. Professor Esty's rules for planning a course in electrical engineering are:

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* An hour in this sense is one hour per week per academic year. This equals about 36 actual hours of lecture recitations, or quiz, or 72 actual hours in the drawing room, laboratory or shop.

1 To teach thoroughly those things in college which are fundamental.

2 To devote little time to highly specialized subjects.

3. To introduce the student to those branches of knowledge which in his later life he can acquire only with increasing difficulty, if at all.

4 To endeavor to cultivate in him the hunger and thirst for more and deeper knowledge, so that he may remain a student throughout life.

**H. W. Buck** presented his views of the education of the electrical engineer from the standpoint of a technically trained practising engineer. In its present state, electrical engineering is the most scientific of all engineering professions. A man must be to a great extent a physicist, a chemist, and a mathematician, as well as being familiar with machinery and its design, in order to be a worker in the broadest field. The best course of training for an electrical engineer would seem to be a broad course of education in general subjects at the preparatory school, then a college course with general subjects during the first year, followed by those general and theoretical subjects that have a direct bearing upon the practice of the electrical profession. This includes such studies as mathematics, mechanics, physics, chemistry, theoretical electricity and magnetism, and thermodynamics. This study should be supplemented by actual daily practical work with machinery operated by the principles covered by the theory studied, and demonstrating all the phenomena incident to the theory. Mr. Buck advocates practical apprenticeship work subsequent to the completion of the college course. In addition to the theory and practice involved in this training, other elements are necessary for the successful engineer. There are many qualities required in common with other professions; executive ability, business knowledge, presence of mind, ability to handle men, nerve, resourcefulness in handling machinery in times of emergency—all these are necessary for the successful engineer. These elements cannot be acquired in the study of theory and practice alone, for many men who have stood high in their college courses have afterward failed in the practice of their profession because of a lack of some or all of these qualities.

**E. B. Raymond.** In another paper at the Great Barrington convention Mr. Raymond proposed the dropping from technical courses of all subjects not of a technical nature, such as language, history, literature, and political economy. The time should be spent entirely upon a theoretical and practical course, which will produce broadminded men with intellect, strength, training, and purpose. To this end the professors should be men of force of character, as well as men of intellectual attainment, and the courses at college should be so arranged that recitation rooms and laboratories could be regarded by the students as we look upon our offices. One of the most essential qualifications of the successful engineer is that he shall be filled with the desire for continual study. After graduation is the time for him to get his knowledge of real detail, amplifying the general knowledge obtained in college by practical investigation.

The discussion on the above papers was even more extensive and interesting than that at Chicago, and indicated an increased interest on the part of practising engineers.

### 1903. ANNUAL CONVENTION, NIAGARA FALLS

At this convention a joint session with the Society for the Promotion of Engineering Education was held. Messrs. J. G. White, Bancroft Gherardi, L. A. Osborne, representing employers of technical graduates, and Professor Dugald C. Jackson presented papers. The consensus of opinion expressed in these papers is that the personality of the technical graduate is of more importance than any information which he may have acquired.

**J. G. White.** The results of a successful education may be summarized as (*a*) the satisfaction which results from possession; (*b*) the ability to enjoy good society; (*c*) the practical use which may be made of the training; (*d*) the ability properly to know any subject, and (*e*) the higher rank which will be taken as a result of this training.

Technical education should produce *engineers*, not students. It should develop not dreamers, but workers, thoroughly competent in their spheres whether great or small. It is better for the world and for the man that he should be a high-class mechanic or artisan, with a good common-school education, than that he should be nominally an "engineer", having a smattering of many subjects. *The importance of thoroughness is supreme.*

The telephone engineer's work is an example of the severe requirements of engineering practice. A few years ago many of us would have supposed that the problems of the telephone engineer were those of a high-class artisan, but a modern telephone engineer must even know something of architecture, the strength of materials, and other factors entering into modern steel building construction, and be familiar with many other subjects not ordinarily supposed to come within the province of a telephone engineer. Other engineers should likewise have a general knowledge of the sciences and of the broad underlying principles of engineering, based upon a thorough mastery of elementary mathematics and supplemented by some study of languages, history, civics, and other studies of general educational value.

**Bancroft Gherardi.** Treating the subject from the standpoint of the telephone engineer, Mr. Gherardi lays down the general proposition that an engineer's qualifications are made up of two factors, personality and training. The training of a telephone engineer should not be essentially different from that of other electrical engineers, the training of any engineer properly consisting of such studies as will convince him of the necessity of getting facts, and teaching him the best method of doing so. Further, these studies should train in the interpretation of engineering data and in reasoning from them. Throughout his paper Mr. Gherardi emphasizes the necessity for relating theory and practice, suggesting that while fundamentals should be the most prominent, examples should be drawn from each branch of electrical engineering to which the fundamental principle may apply. In this way the value of the principle will be borne in upon the mind of the student. He will be helped to see theory and practice in the proper perspective, and will be aided in deciding upon the particular branch of engineering for which he is being fitted. The examples will also not be without some practical value in his early professional work. In regard to his experience with technical graduates, Mr. Gherardi states that the training they receive, notwithstanding its imperfections, is of great value to them and to those for whom they work.

**L. A. Osborne** impresses the facts that the large majority of young technical graduates are not fitted by temperament or training for pure engineering work, and that they regard it only as a stepping stone to business. At the same time the teachers of these men have proceeded on the assumption that they would be ultimately engaged in engineering. He therefore advocates the broadening of courses to the end that the whole body of engineers will enter upon their work with a fuller comprehension of its duties and opportunities. Mr. Osborne contends that shopwork should be taught with a view to training the student in the principles which underlie the tool organism of a shop. He should know more about the functions of tools, the principles of their design, and their relations to each other. While it is true that familiarity in these lines comes largely from experience, the author infers that the schools can have a share in providing it. Works-accounting, the problems of capital and labor, the law of contracts, and other such apparently non-engineering subjects should not be neglected in the engineering curriculum.

**Dugald C. Jackson**. Professor Jackson calls attention to the fact that since he brought up the subject in 1892, the sentiment regarding college men has entirely changed. These men have become influential in engineering practice. The business of the engineering colleges is to produce, not finished engineers, but young men with a great capacity for becoming engineers. The names attached to the subjects taught are not very important as the results produced by the teaching, namely, the effect produced upon the students, show. The ideal engineer is competent to conceive, organize, and direct extended industrial enterprises of broadly varied character. He must be a keen thinker with an extended knowledge of natural laws, and an instinctive capacity for reasoning from cause to effect. He must also know men and their affairs, business methods, and the affairs of the business world. The ideal course in electrical engineering should include the following underlying training.

1. That fuller training in the construction of the English language which is requisite to clear thinking and clear writing, preferably accompanied by an additional language for added strength.
2. The collateral art of expression in drawing.
3. Mathematics through an appropriate amount of calculus, including the integration and solution of equations involving derivatives, and instruction in the use of co-planar vectors, and perhaps quaternion quantities—all of which should be taught as applied logic with special emphasis laid on interpretating the meaning of equations.

4. The science of chemistry, soundly taught.
5. The science of physics soundly taught, with particular emphasis laid on the elementary mechanics.
6. Applied mechanics.

Mechanics—the philosophy of matter, force, and energy—is the backbone of the electrical engineer's college training.

He also outlined laboratory and practical courses, which should accompany the fundamentals. He deprecated the use of descriptive courses as having a tendency to neutralize the advantage resulting from instruction in fundamentals.

The work in electrical engineering should be divided into: applied electromagnetism, the theory and practice of alternating variable currents, applied electrochemistry, electrometallurgy, and electrical installations.

In analyzing the courses advertised in college catalogues Professor Jackson finds three varieties of instruction. In the first of these, electrical engineering is taught as an illustration of the beauties of nature, rather than of its great underlying laws. The instructors in these courses are out of touch with the industrial world. The second class of instruction is apparently intended to train inexperienced students to assume positions of responsibility and large remuneration. The third variety of instruction approximates the ideals laid out in the paper. In closing, Professor Jackson states that many of the greatest weaknesses in engineering courses are that the heads of colleges or universities do not understand what engineering truly stands for, and they often have no fair conception of the soundness of training that is required for its practice.

### 1903. SEPTEMBER MEETING

**Chas. F. Scott,** in his inaugural address as president proposed that universities and technical schools with educational engineering departments should hold local meetings of the Institute for benefiting both instructors and students by keeping them in touch with recent developments and practice. It is argued that theoretical training in fundamental principles should predominate and that such Institute meetings will enable the student to keep in touch with actual things and give him a more adequate idea of the career for which he is preparing. It will supplement his theoretical training, making it definite and certain, so that he may properly assimilate the instruction he receives. It will show him that the electrical engineer needs much more than mere technical training, and it will tend to make his college work less abstract and more concrete and efficient.

### 1907. ANNUAL CONVENTION, NIAGARA FALLS

**Henry H. Norris.** At this convention education was the subject of two papers; one by Professor H. H. Norris, the other by Professor V. Karapetoff. In Professor Norris' paper emphasis was laid upon the elements of personality in the technical students. The elements of success in technical training are:

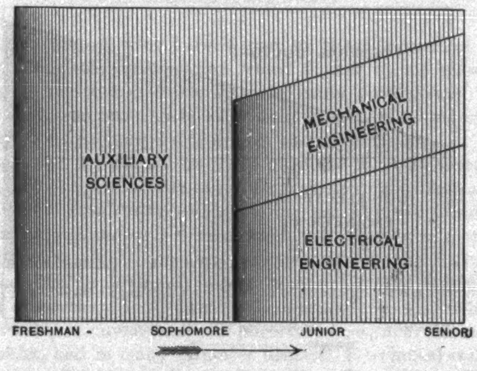
1. The attraction and retention of desirable students and the exclusion of those not qualified for technical work,

2. The selection of such studies as will stimulate and direct mental activity.

3. The conducting of all courses in such ways as will tend to bring out the desirable personal qualities in the students.

4. The recommendation to the students of those lines of engineerin practice for which they are best suited.

In developing the subject the author made use of a magnetic analogy of a technical training. The mind of the student was compared to a piece of magnetic material which possesses the ability to be magnetized on account of the inherent magnetism of its molecules. A piece of iron or steel is magnetized when its intrinsic qualities are subjected to a direct magnetomotive force. In a similar manner the young men entering the technical school possess certain elements of personality. The function of the instruction is to supply the directive force necessary to bring out the student's latent qualities. The student gets little that is new from his college course, and if the attempt is made to impart to him more information than is necessary to stimulate him to his best endeavors, mental saturation results. The writer traces the history of the technical school, and refers in some detail to that of Sibley College, which with the Massachusetts Institute of Technology was a pioneer in electrical engineering instruction. The present curriculum of Sibley College was outlined in order to permit it to be compared with the ideals laid down. In order to indicate the lines of work taken up by technical graduates an analysis of the present occupations of the numbers of graduates of Sibley College was given.



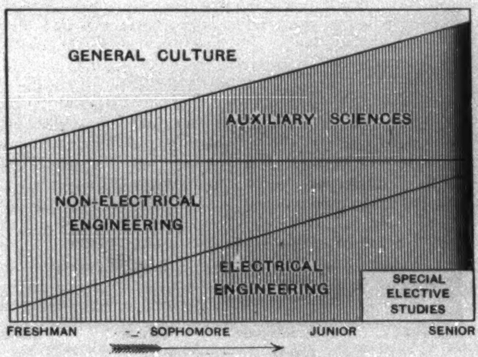
**Vladimir Karapetoff.** In his paper "On the Concentric Method of Teaching Electrical Engineering" Professor Karapetoff outlines a four-year college course different from the usual courses in two respects:

1. The course begins with the practical descriptive side of engineering and gradually leads into the theory, contrary to the present system, which begins with the theory.

2. Each year is made as far as possible self-contained, so that the student's horizon is gradually " concentrically " widened, and he is prepared for lower practical positions after the very first year in the college.

Moreover, according to this method, the student does not need to select a particular branch of engineering the first, or even the second year. In the first year he gets a " cyclopedia " of electrical, mechanical, civil, and mining engineering, and is given a chance to judge for himself which branch he likes the best. In the second year he is again given an opportunity to select between the mechanical and the electrical engineering. In the third year he gets straight electrical engineering; and in the fourth year specializes in the mathematical and physical theory of his profession. He also chooses a few elective branches, such as electric railways, telephony, power transmission, design, etc.

The advantages claimed for the above arrangement of the courses are as follows:



1. The student selects his profession after having had an outline course in it, in parallel with a few other allied specialties.

2. The method of beginning with the practical side, in other words with the ultimate results, is more psychological than beginning with abstract auxiliary sciences.

3. The interest and the professional feelings in the student are early aroused.

4. He can spend his vacations more profitably, having had engineering courses from the start; he can also be interested in technical literature and societies earlier than is possible with the present method.

5. A possibility is created for producing " learned artizans " who have taken one or two of the early years, and may then be useful in practice as assistants, or can do independent work in newly opened parts of the country, etc.

6. The theory, being built on the known facts of experience, will be less abstract, and more in unity with the requirements of practice.

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# ELECTRICAL ENGINEERING EDUCATION

BY CHARLES P. STEINMETZ

When in the following I dwell more on those features of our electrical engineering education which appear to me unsatisfactory, it is not that I overlook the many good points, but rather that a criticism of the few defects appears to me more important, for the purpose of urging their elimination.

In general, the conditions for a good electrical engineering education in the United States are far more favorable than anywhere else; for an electrical engineering industry developed to a higher degree and to a greater magnitude than in any other country offers a very large field of application to the graduate engineer, thus supplying an incentive to enter this profession. Unlike other countries, where some opposition to the college-trained man, as unpractical, still lingers, the electrical industries here prefer, and in many instances demand, a technical college training for their engineering staffs. There is a tendency now to demand this training even for administrative and commercial positions. This leads to a close coöperation between the electrical industry and the engineering college. The leaders of the industry take a close and active interest in technical educational work, while teachers of engineering consider it as their foremost duty closely to follow and keep informed of the advances of the electrical industries, sometimes even are actively engaged in industrial work; and as early as possible the students are introduced to the industry, by visits to factories, inspection trips etc., which become more and more an important part of the college education. This is as it should be, and probably constitutes the strongest features of American engineering education.

While many, especially smaller colleges, are not financially strong, in general the means available to the American college of engineering are far superior to those abroad, and especially in erecting engineering buildings, laboratories, etc., much has been done.

The great defect of the engineering college is the insufficient remuneration of the teaching staff: the salaries paid are far below those which the same class of men command in industrial work, and as a result the college cannot compete with the industry for its men, but most of the very best men are out of reach for the colleges. The teaching forces of the colleges therefore consist of: 1. A few of the very best men, who are specially interested in educational work to such an extent that they are willing to sacrifice financial returns for it. These men have made the engineering college what it is, but even many of these men are ultimately forced by considerations of family, etc., to leave college work and enter industrial employment. 2. Many younger men interested in teaching, enter college work to give it a trial. Some of these remain, but many return to industrial work, when they are forced to realize the small prospect of financial return offered by the college. 3. First-class men who devote a part of their time to the college and a part to industrial work, usually consulting engineering. This arrangement is probably the best for the college, handicapped as it is by the policy of salaries which may have appeared sufficient in branches in which no industry competes, but which are suicidal in the engineering department. Still it would be far preferable if the colleges could get the benefit of the whole time and the undivided interest of these men.

It appears to me, therefore, that a vast improvement could be made in electrical engineering education if a large part of the sums which now are devoted to marble engineering buildings and fancy laboratory equipments could be devoted to offer such salaries as to make available to the colleges the undivided time and interest of the best men in the field. The name of the donor may just as well be perpetuated by the professorship which he endows, as by the pile of marble which he erects for the college. After all, engineering buildings and college laboratories are of very secondary importance compared with the qualifications of the teacher and his assistants.

To the subjects taught and the methods of teaching very grave objections may be made. The glaring fault of the college curriculum is that quantity and not quality seems to be the object sought: the amount of instruction crowded into a four years' course is far beyond that which even the better kind of student can possibly digest. Memorizing details largely takes the place of understanding principles, with the result that a year after graduation much of the matter which had been taught has passed out of the memory of the student, and even examinations given to the senior class on subjects taught during the freshman and sophomore years, reveal conditions which are startling and rather condemnatory to the present methods of teaching.

It stands to reason that with the limited time at his disposal, it is inadvisable for a student to waste time on anything which he forgets in a year or two; only that which it is necessary to know should be taught, and then it should be taught so that at least the better student understands it so thoroughly as never to forget it. That is to say, far better results would be obtained if half or more of the mass of details which the college now attempts to teach, were dropped; if there were taught only the most important subjects—the fundamental principles and their applications—in short, all that is vitally necessary to an intelligent understanding of engineering, but this taught thoroughly, so as not to be forgotten. This, however, requires a far higher grade of teachers than are needed for the mere memorizing of text-book matters, reciting them, at the end of the term passing an examination on the subject and then dropping it. The salaries offered by the colleges are not such as to attract such men. When the student enters college he is not receptive to an intelligent understanding, for after a four years' dose in the high school of the same vicious method of memorizing a large mass of half and even less understood matters, the student finds it far easier to memorize the contents of his text-books than to use his intelligence to understand the subject-matter. After graduation, years of practice do for the better class of students what the college should have done—teach them to understand things. It is, however, significant that even now young graduates of foreign universities, in spite of the inferior facilities afforded abroad, do some of the most important electrical development work of this country. Men who never had a college education rise ahead of college graduates. This would be impossible if our college training gave what it should, an intelligent understanding of electrical engineering subjects.

The cause of the fault is perhaps the same that leads to the erection of engineering buildings and laboratories while underpaying the teaching staff: the competition among the colleges. To the father who looks up a college for his boy, marble engineering buildings and fancy laboratories are impressive, and so is an extensive curriculum; the result is a rapid increase in the number of students; but it is not to the benefit of the student, since the faster a subject is learned the faster also it is forgotten, and to become and remain thoroughly familiar with a subject, it is necessary to keep up the study of it for some years. While it is a good feature to insure application of the student by term examinations, etc., this becomes harmful if it leads to dropping the subject at the end of the term. The least that can be expected from the college is that at the time of graduation the student still knows all that he has been taught during his college years. To accomplish this it is necessary to keep up the study of every subject to the end of the college course. This is not the case at present.

The different colleges vary between the school teaching the trade of electrician, and that attempting to give an intelligent electrical engineering education. At the one extreme is the college which dropped from its curriculum everything not required in electrical engineering. Such a school covers a large ground in electrical engineering, may even consider shortening the course to three years. The graduate of such a course is a full-fledged electrical engineer, capable to ply his trade, just as a plumber or brick layer when graduating from his apprentice years, and just as helpless and useless when any occasion arises requiring general knowledge to enable him to understand matters beyond his trade. The unavoidable result of such training is, that when with the development of the industry subjects become of importance which were not considered as pertaining to the trade of electrical engineering during his college years, his usefulness is impaired, younger men rise above him, and he cannot hope to rise beyond a subordinate position. Fortunately, the better technical colleges realize that the first requirement of an electrical engineer is a thorough general education, and begin to realize that for this purpose it is not sufficient to require general subjects for college entrance and relegate their study to the high school: for even if the average high school were what it should be and not what it actually is, much of the general knowledge required by an educated man cannot be taught in the high school, since during the high-school years the intelligence of the boy is not sufficiently ripened for its grasp, and a review in the college is necessary.

However, even if an attempt is made to teach or to review general subjects, the work is not carried sufficiently far. Mechanical engineering, physics, chemistry, and some civil engineering subjects are recognized as legitimate subjects of teaching in the electrical engineering course in many colleges, together with literature, some history etc.; but physiography, physical geography, meteorology, mineralogy, astronomy etc., are also of importance in a general engineering education. The failure to recognize this may sometime be a severe handicap to the electrical engineer, and that in the not very far future, judging from the present trend of development. In this direction the student, as well as his parents, are frequently antagonistic, and cannot see why subjects should be studied, which to their limited horizon appear unnecessary.

The instruction given in those branches of science, a knowledge of which is required by the electrical engineer, but to which only a limited time can be devoted, as chemistry, civil engineering etc., frequently is very unsatisfactory, being unsuited to the requirements of the electrical engineer, and, as a result, of very little if any value to him. A general knowledge of these branches is required, so as to familiarize the electrical engineer with the general problems, methods, and purposes of the science; to enable him to understand subjects dealing with these sciences. The ability actively to practise the science is not required. To illustrate in the case of chemistry: the electrical engineer should have a knowledge of the laws of chemistry, a familiarity with the elements and their compounds, and a general knowledge of the methods of analysis and synthesis. Such a course must, therefore, necessarily be largely descriptive, and the experimental work largely illustrative. The same course is frequently given to the electrical engineer as to the first few terms of the chemistry student: general inorganic chemistry of the most important elements, and qualitative analysis. While a first-class beginning of a course of chemistry, such a course leaves the engineer with a knowledge altogether too fragmentary to be of benefit to him, and the time spent in mastering the mechanism and the details of qualitative analysis is largely wasted, since the electrical engineer will probably never be called upon to make an analysis. If he attempted to do so he would probably fail. The beginning of a chemist's training is not suited to the chemical training of the electrical engineer, and the same applies to all other sciences to which a limited time is devoted in the electrical engineering curriculum. To give a general view and working knowledge to the electrical engineer of such an allied branch of science, theoretical discussions, especially mathematical, are usually very little needed and therefore undesirable. A characteristic case of spoiling a science to the student by mathematics is that of astronomy. Astronomy is one of the most interesting and fascinating of subjects. But where taught as a part of the general educational program, it frequently is all mathematics, and so hopelessly dry and repellent. It should be given descriptively, for in a short course on astronomy it is just as ridiculous to delve deeply into mathematics as it would be to start the teaching of geography with a course in spherical trigonometry. I believe that in the teaching of allied sciences our colleges and schools are still greatly inferior to those abroad; the result is very marked in the product of the colleges, in the inferiority of the general education possessed by our graduates.

It goes without saying that in all teaching the strongest endeavor should be made to correlate the different subjects, to show the students the close relations which exist between all the branches of science, no matter how different they appear at first sight; and to interest him by bringing home to him the practical importance of what otherwise would appear dry theory. For instance, by using in the teaching of mathematics, problems taken from engineering; to have him handle and operate machines before proceeding to their theoretical investigation; then to derive the constants of the theoretical investigation from experimental tests of the apparatus; and from these predetermine the performance of the apparatus under different normal and abnormal conditions and experimentally verify it.

In conclusion, the main defects in the present electrical engineering training in some of our colleges appear to me as follows:

1. The insufficient remuneration of the teachers, which makes most of the best men unavailable for educational purposes and is, therefore, largely responsible for the other defects.

2. The competition between colleges, which leads to a curri-

culum marked more by the quantity of the subjects taught than by the thoroughness of the teaching. The graduates are sent out with a mass of half understood and undigested subjects, quickly forgotten, and deficient in understanding of the fundamental principles and in the ability to think.

3. The tendency of some colleges to teach the trade of electrical engineering rather than educate intelligent and resourceful electrical engineers.

4. The unsatisfactory state of the teaching of allied sciences, which gives instead of general view and understanding of the science, a fragmentary knowledge of some details.

## DISCUSSION ON "THE EDUCATION OF THE ELECTRICAL ENGINEER." NEW YORK, JANUARY 24, 1908.

**Charles F. Scott:** Since preparing this short paper which I intend to present this evening, I have taken part in a symposium on "The Teaching of Mathematics to Engineeers" at a joint meeting of the Chicago Section of the American Mathematical Society and the Mechanical Section of the American Association for the Advancement of Science. My contribution seems to me so pertinent to the educational questions now under consideration that I shall present it here.

Mathematics, from the standpoint of the engineer, is a means, not an end. It is an instrument or tool by which he may determine the value and relations of forces and materials. The usefulness of tools depends upon the sort of work which is to be done, upon the kinds of tools which are available, and upon the skill of the man who uses them. We may inquire, therefore, what are the uses to which the engineer may apply mathematics? What kind of mathematics does he need? And what skill should he possess in their use?

First, then, what work is to be done by the young men who are now taking engineering courses? A few—and only a few—will be original investigators or designers who will need mathematics as an instrument of research. A considerable number will regularly employ elementary mathematics in more or less routine calculations. Many will have little use for mathematics, as engineering courses are recognized as affording excellent training for various business, executive, and other non-technical positions, particularly in connection with manufacturing and operating companies. It has been said by the vice-president of a large electric manufacturing company that not over 10 per cent. of the technical graduates employed by that company are fitted by temperament or by education to take up with success the work of pure engineering. A recent classification of the graduates of Sibley College, Cornell University, shows that about 50 per cent. are in occupations which require no advanced mathematics, and it is probable that many of the 36 per cent. classed as mechanical and electrical engineers seldom go beyond the rules of arithmetic. Hence a goodly proportion of engineering graduates do not need to be mathematical experts. Their mathematical studies should not aim to produce experts, but should have as a principal object the mathematical training which is a most efficient kind of training in an engineering course. On the other hand, the engineers who will have practical use for the higher mathematics will find their ability as engineers is in a large measure determined by their ability as mathematicians.

Secondly, what kinds of mathematics does the engineer need? This is closely related to the class of work he is to do. In general, a great deal of engineering work is done with much less use of higher mathematics than most professors probably imagine, and furthermore, it may be remarked, with much less than could profitably be employed. Engineers are apt to use ordinarily the mathematical methods with which they are most familiar and which will bring the result with the least effort. One man employs calculus, another draws a diagram, another writes out formulas, while still another gets his results by mental arithmetic. The object is to get the result. The fundamental idea that mathematics is something for the engineer to use finds many illustrative analogies in ordinary tools.

Adaption is the first requisite; tools should be suited to the work to be done. An expensive machine-tool with its refined adjustments is quite unnecessary for executing a piece of work which can be done with sufficient accuracy by a few minutes' application of a file. In every-day work an ordinary calculating slide-rule is infinitely better than a table of seven-place logarithms. On the other hand, it is particularly wasteful to attempt to execute a difficult and intricate piece of work with inadequate tools. But more important than the tool is the skill of the man who uses it. A skilful workman can accomplish results with a few simple tools which another cannot get with the most elaborate special equipment.

Thirdly, therefore, skill in the use of mathematics is the really essential thing. A judicious use of arithmetic with a little algebra or a simple diagram often leads to more satisfactory results than others obtain through elaborate processes involving lengthy equations and complicated operations. In the latter, errors are liable to occur; the common-sense import of the problem is apt to be overlooked; assumptions may be made to facilitate calculations which are physically unwarranted, as one loses sight of the physical problem in the intricacy of the mathematical solution. Abstract mathematical studies, if pursued as a kind of intellectual callisthenics, may produce a pure mathematician, but they may unfit a man for practical engineering. A mathematician is not necessarily an engineer, nor is an elocutionist necessarily a good lecturer, nor a tool expert a successful manufacturer.

Mathematics is used in engineering to express the quantitative relations of natural phenomena. The mathematician delights in the relations; he divorces them from the phenomena and gives them abstract expression. But the engineer is concerned with the natural phenomena: he demands the physical conception; the medium of expressing these relations is of secondary consequence.

The mathematician evolves the equation for a parabola and finds a convenient illustration in the law of projectiles. The engineer finds that a physical result follows from the application of certain forces, and uses the formula merely as a convenient method of expressing the law. The analogue in the case of mechanical tools is found by regarding a set of drawing instruments or a transit or a lathe, as something intelligently designed, properly proportioned, accurately made, and finely finished, the merit of which lies in their own inherent excellence, or, on the other hand, by considering them as tools adapted for doing a certain range and character of work with a sufficient degree of accuracy and at low cost.

A manual training school gives familiarity with mechanical tools, and mathematical study gives familiarity with intellectual tools. In working with the manual tool, the boy uses it for making something; by making something, he learns the principle on which it operates and the way to use it. If the thing made is something useful, it awakens a keener interest than perhaps would some fancy device. Likewise training of engineers in mathematics should be by doing something, by the solving of problems, by dealing with real rather than abstract conditions. Let this training be obtained while applying mathematics to its normal and legitimate purpose as an auxiliary to the study of other branches.

In the teaching of mathematics for its own sake stress is apt to be laid upon the processes of deriving results rather than the real meaning of the results themselves. An engineer who uses logarithms has no more concern regarding their derivation than the ordinary user of the dictionary for finding the pronunciation of words has in their etymological derivation. The ability to reproduce demonstrations in higher mathematics from memory with the book shut is often not as important as it is to understand them with the book open. In general, an engineer who has occasion to use higher mathematics, will not be interested in evolving difficult equations, nor will he appeal to his memory; but with text-book or reference before him he will seek the things he wants to use. He should know where to find them and how to use them.

In emphasizing what a skilled mechanic can make with very ordinary tools, or the true engineer can accomplish with the parallelogram of forces and the rule of three, there is no intention of discrediting the value of fine equipments both mechanical and mathematical if there be the ability to use them.

Possibly the practical utility of mathematics may appear to be urged too strongly, particularly as the writer really believes in thorough mathematical training; but he has seen so many cases in which mathematical instruction has never been digested and assimilated, so many simple mental processes confused by unnecessary mathematical complications, so many men satisfied with results which are absurd because of some mathematical equations, sometimes quite unnecessary—that a common-sense perspective view of ordinary things seems to need emphasizing. He recalls the new insight into mathematics which came through the study of analytic mechanics under Professor S. W. Robinson at the Ohio State University, and problems in mechanics under Dr. Fabian Franklin at Johns Hopkins University, that he feels there is little danger in over-emphasizing the importance of concrete training in mathematical study.

The practical questions which the discussion of this subject presents are these:

1. What mathematical subject-matter should be covered?
2. How should it be taught?

The first difficulty is that there is not, and cannot be, a differentiation in technical education which is at all comparable with the wide range of occupations into which graduates will enter. We may assume, therefore, that we are considering the case of the average engineering student, taking for granted that options may be used by the best students to enable them to take up the more advanced and difficult mathematics. Obviously, the student should have enough mathematics to enable him to demonstrate the important engineering laws and formulas, and to read intelligently mathematically written engineering literature. While only the relatively simple mathematics is commonly used by engineers, yet the ability to handle new problems with confidence requires a thorough understanding, and appreciation of the significance of the mathematical and physical basis of the laws and phenomena he is to use. A man who is a thorough mathematician and knows how to apply his knowledge has a great advantage over the pure mathematician or the man without mathematical training. The better knowledge one has of the complex, the more certainty he has in applying the simple. A student should understand something of the power of the advanced mathematics and the field of their efficient application. Although he may not be expert in using them himself, he will know when to call for a mathematical expert.

An engineer of fairly wide experience remarked a short time ago:

> The ordinary engineer does not use higher mathematics because he doesn't know how. He does not have the proper conception of the fundamental principles of the calculus because the subject has been taught by men whose ideals are those of pure mathematics.

If mathematics is something for engineers to use, let their use be taught to engineering students. After the fundamentals are learned, the students should attack the engineering problem at once and bring in mathematics as a means of solving it. Mathematics is often advocated for developing the reasoning powers and the ability to reason from cause to effect; there is danger, however, that mathematical machinery may make the mere process obscure the cause and the effect. Let cause and effect be foremost, with the process secondary or auxiliary to them. The way mathematics is brought to bear on some engineering problems reminds one of the story of the old lady who greatly admired her preacher because he could take a simple text and make it so very complicated.

Old traditions have not wholly disappeared; the fear of de-grading the pure science of mathematics by applying it to useful things still lingers—in influence, if not in precept. We must go further and adapt mathematics to engineering, not only in subject-matter, but in method. A mathematical teacher with no patience for anything except mathematics will probably teach a kind of mathematics which has no connection with anything except mathematics. Engineering mathematics may be better taught as a part of engineering by an engineer, than as a part of mathematics by a pure mathematician. The maker of levels and transits who is expert in the construction of the instruments and an enthusiast over the accuracy of the surfaces, the excellence of the bearings, the near approach to perfection in the graduation, and the general refinement and beauty of workmanship, may make a good instructor on instruments, but a poor teacher of civil engineering.

After all, it is not so much abstract courses as it is men with which we have to do; it is not mere knowledge of facts or facility in mathematical manipulation, but it is training. The young man is to be developed; his native individuality is to be the basis; he is to increase not only his knowledge but his powers and the ability to use them. It is not mathematical skill so much as a mathematical sense, or mathematical common-sense, which is wanted. With pure mathematics as a science we have no quarrel—and little affiliation.

We are concerned with applied mathematics. The ability to state a problem; to recognize the elements which enter into it; to see the whole problem without overlooking some important factor; to use good judgment as to the reliability or accuracy of the data or measurements which are involved; and, on the other hand, the ability to interpret the result; to recognize its physical significance; to get a common-sense perspective view of its meaning and the consequences which may follow; to note the bearing of the various data upon the final result; to determine what changes in original conditions may change a bad result into one which is practical and efficient—such abilities as these are of a higher order than the ability to take a stated problem and work out the answer. It may be urged that all this is not strictly mathematics. But it is just this sort of judgment and insight which makes mathematics really useful, and without them there is danger that they may be neither safe nor sane.

If you ask men who use engineering graduates what qualities they should possess, you will find that special prominence is "common-sense" and "the ability to do things." In mathematical training it is quality rather than quantity which is of first consequence. Mathematical training should develop a faculty for systematic and logical reasoning, thus furnishing a general method as well as a specific means of getting results.

The trend in education is to a closer relation to the affairs of life. Science and applied science, scientific and engineering laboratories are overcoming old ideas and prejudices. Modern engineering development brings its transforming influence to bear upon education as well as the utilities of modern life. The engineering school has had a phenomenal growth within the lifetime of the recent graduate—a growth in ideals and methods as well as in students and equipment. It has raised and agitated broad questions as to what constitutes efficient education for producing effective men. It has aimed to combine not only the abstract with the concrete, the lecture room with the laboratory and the scientific experiment with the practical test; but it has sought by various means to bring the work of the school into close relation with active professional and commercial practice. It has a definiteness of aim and purpose which other educational courses are apt to lack. It sets out to produce men who can deal with forces and materials according to scientific principles. It develops men whose contact with physical facts and natural laws at first hand and whose ability to reason logically fit them for dealing with new problems. The training which fits men for handling engineering problems is the kind that is needed for dealing with the organizing and directing of men. The sphere of the engineer is one the scope of which will continue to increase as engineering education and training produce men whose contact with natural phenomena gives them an inherent respect for facts as their premises, who are able to think straight to logical and commonsense conclusions, who have an equipment of technical knowledge and who can produce results.

In discussing the teaching of mathematics to engineers, we should emphasize not the mathematics nor the engineers, but the teaching. Aside from the imparting of knowledge and technical ability, the teaching of mathematics gives opportunity for training in the use of logical methods and in the drawing of intelligent conclusions from unorganized data which will make efficient men, whether they follow pure engineering or semi-technical or business pursuits. Such teaching does not come from the text-book; it must be personal—it comes from the teacher. He must be in sympathy with engineering work and have a just appreciation of its problems and its methods. He must be imbued with the spirit and the ideas of the engineer.

**Chas. P. Steinmetz:** I agree with Mr. Scott in the relation of mathematics to engineering. I agree with him also that mathematics is a tool, the most important and useful tool of the engineer; but it is useful and valuable only as long as it is a tool, and ceases to be useful as soon as it goes beyond a tool and becomes a purpose. Mathematics becomes not only useless but positively dangerous as soon as the user does not fully and clearly see the physical meaning of every mathematical step he takes, or fully appreciates the physical meaning of every step when reading through a mathematical derivation of a result. As soon as one understands the physical meaning of every step, one can, as a rule, greatly simplify the mathematics by skipping complex mathematical reasonings by a short cut based on common-sense. For instance, instead of carrying the calculations through with the positive and negative signs of a square root, one can frequently say: for physical reasons, the sign must be positive, and drop the negative, or inversely. Mathematics is merely a shorthand method of recording physical intuition and physical reasoning, but it should not be a formalism leading from nowhere to nowhere, as it is likely to be made by one who does not realize its purpose as a tool.

**L. A. Osborne:** One may very easily assume a dogmatic attitude in giving expression to opinions upon the subjects treated of in to-night's papers. That is a state into which we are very prone to fall, and in the interest of real progress it is important that we should avoid it.

As engineers we are quite content to accept criticism from the layman of the structures which we build and plan, but when he attempts to tell us how to fashion our productions to accomplish the result which he requires, then we rise up and object. I feel this way about commenting on engineering education.

Some years ago I was persuaded to express my views upon this subject, which I did before this body, and I made up my mind never to venture upon such slippery ground again. The cries which went up from some of my academic friends led me to this renunciation, although there was an occasional friendly word which relieved the situation of utter hopelessness. That was several years ago. Now there is some satisfaction in knowing that some of the views expressed in my paper have since been adopted, and in a number of cases I have been accorded more credit than I deserved as the originator of some of the ideas there advanced.

I do not believe in telling the teachers how to do their work; I think we should better state what the finished work lacks. I am a product of the engineering educational methods in vogue fifteen or twenty years ago, and have long been what might be termed a purchasing agent for the consumer of the products which the schools turn out. I have thus been able to note certain tendencies, the resultant effects of which have left on my mind a sort of composite picture of the technical graduate as he has passed before my vision for the last ten years. While individuals may have qualities which set them apart from the crowd, still the average impress of the whole is that which produces the composite effect, the one which remains with me. Without presuming to point out how the quality can be improved, I recount here certain impressions which remain from my experience:

First, that 50 per cent. of the technical graduates that present themselves to be employed might better never have undertaken their profession; that at least that proportion of those with whom I have come in contact have apparently chosen an engineering profession more in the hope of the emoluments and not from any real interest in or love for the work.

How the real engineers can be detected in the first instance is a matter beyond me; but it is quite certain that a process of elimination which will put into the engineering classes men earnestly loving their chosen work, would not only make those men better fitted but would be a greater inspiration to the profession and a greater credit to their colleges.

Secondly, that of all those who remain, who may be termed good promising timber, the chief fault that I have to find with them, is that they are generally unable to grasp abstractions, that they are unable to generalize. Inasmuch as engineering *per se* is a profession dealing with specific problems, the tendency which follows application to its studies leaves the individual less able to treat with generalities. This is a question, therefore, of injecting into the courses something which will stimulate the powers of generalization which, broadly speaking, is more general culture.

Professor James has written very entertainingly in a recent magazine issue on the subject, " Of what use is a college education ", and the answer there given is the answer to apply here, but perhaps in a more restricted sense. Professor James contends that a person having the advantage of a collegiate training is better able to discriminate between the good and the bad in mankind. To the engineer, his training should give him that fine degree of discrimination which enables him to know what is good and bad in engineering, and inasmuch as engineering has become so important an adjunct to our everyday lives, the engineer should likewise have the discrimination to enable him to judge between the good and bad in mankind itself. We want men who know good jobs when they see them, whether the job is man-made or made by nature in the form of man himself. Engineers to-day are too self-centered; too bound up in the details of their profession. They are not as a rule men of the world but are men in the world with a too narrow perspective, largely due to the fact that their early training did not stimulate them in the right direction.

**H. E. Clifford:** There is at this time a very general agreement as to the advantages of a broad training for electrical engineering students, a training involving both breadth and depth. We do not want a training that is so broad as to be superficial. We want a training which is well proportioned as to breadth and depth. It is interesting, I think, to note that a basis of science and cultural studies for engineering education was specifically stated by President Rogers, the founder of the Institute of Technology, in his application for the charter for that institution, and I distinctly recall the very strong emphasis which General Walker, during his presidential career with us, laid on these particular foundation stones of engineering training. There is, however, one danger, as it appears to me in this general agreement as to breadth of training, and that is the danger of the tendency to standardize education. It seems to me it would be a most serious drawback should this Institute or any body of men attempt to standardize educational methods. Education is not as yet more than an art, it is not an exact science; and standardization, while it may do for apparatus, certainly should not be applied to education.

The personal element has been emphasized in Dr. Steinmetz's paper. I think that is one of the highly important points to consider. A poor system may be made effective by a good teacher, and a good system can be ruined by a poor teacher. It is, after all, the personality of the teacher that accomplishes results. I may mention in this connection what has always appealed to me as a branch of research, as truly important as the research on inanimate things, namely, the research which the teacher certainly carries on in his investigation of a problem in teaching, as distinguished from a problem, it may be, in chemical or engineering investigation. There are many teachers, as there are many so-called research men, who are inadequately prepared for their work, who can carry out their teaching as research only under direction; in other words, they merely work along suggested lines but are not properly research teachers; but I do believe that research in teaching is an important branch of scientific investigation. After all, education has for its primary object the training of men to think straight, to think logically; and the particular type of education, whether it be civil engineering, or electrical engineering, or chemical engineering, is merely a medium for bringing that thing about. Teaching of men to think logically can be frequently, and is undoubtedly frequently accomplished by training which is absolutely non-engineering in character. I think that is the reason why very often college men without any technical training whatsoever handle the larger problems of engineering more successfully and satisfactorily than some of our men highly trained from a technical point of view. This teaching of men to think straight, to think from cause to effect, must be carried out both in the class room and in the laboratory. No amount of training will help some men. Genius is not developed in a technical school unless there be some spark to begin with, and men without capacity, I believe, should be eliminated early.

I believe that many of our educational institutions are inclined to be too lenient in cutting out men who have no place whatever in engineering education, and I believe that a distinct step forward would be made if we should attempt to eliminate from the student body early in the course those men who convince us absolutely of their inability for the line of work which they have chosen. By eliminating these men, we should then have a class made up of men of exceptional ability and men of average ability. I would go further and suggest the segregation of the men of exceptional ability and the men of merely ordinary ability. I do not mean by this that I would put in the exceptional class the so-called—if I may use the college term—"greasy grind" type of man; but I mean the man who shows he has a broad outlook, keen intellect, real power—not the man who has intellectual facility which is quite apart from intellectual power. You may say, how are you going to tell such men? I believe that a good teacher can, to a great degree, discriminate between a man of merely ordinary ability, and a man of exceptional power; and I believe if this system were adopted that the results in producing men of the higher class of engineers would be very much superior to what exists to-day where men of moderate ability and men of superior ability are kept together and carried along in precisely the same way through a particular system of training. This would lead, also, I believe, to graduate work, a most important influence, and one which the technical schools have not begun to build up to the extent the importance of the subject demands.

Dr. Steinmetz also speaks of the importance of securing teachers from the open market. I believe that is also a very important point. The personal element is, after all, of paramount importance in teaching; and it seems to me absolutely essential that men should be secured and remuneration given which will enable these men to devote their time wholly to the problems of education. I do not mean that they are not to keep in contact with engineering progress; but there is great danger that a man who is trying to ride two horses will fall between the two. Teachers should keep in contact with engineering progress, but they should also devote their main interests to the educational side.

In regard to the matter of contact with engineering, some three or four years ago I gave considerable thought to this particular point, and it seemed to me it would be a very helpful thing if the interest, the knowledge, the breadth of view of consulting engineers could be brought into contact with the instructing staff of an engineering department. I suggested at that time to the authorities of the Institute of Technology the appointment of a committee of consulting engineers, and after due deliberation that committee was appointed. I believe that is going to be extremely helpful to us in bringing into the department the ability of men—just such men as Dr. Steinmetz refers to, men of force, men of standing in the engineering world, but who have the interest of the industrial rather than the teaching side of the subject first at heart.

In regard to thinking straight, I believe, as applied to the laboratory system, that every laboratory experiment should be made so far as possible a distinct engineering problem. It seems to me that the satisfaction which the students of to-day show in the *mere performance* of laboratory experiments is a very serious menace to the success of our laboratory system.

Along these lines I suggested some three or four years ago a scheme of having every student in his laboratory work present a formal preliminary report of the scope of his investigation, the instruments needed, the particular scheme of operations, the results to be accomplished and their significance in the performance of the piece of apparatus being studied. This report is examined by some member of the instructing staff in consultation with the student before the work in the laboratory is performed, thus giving the opportunity for emphasizing fundamental principles and the advantage of personal contact of student with instructor. That is the system we are using at the Institute of Technology to-day and we find that it works infinitely better than the ordinary system of the mere perfunctory performance of laboratory experiments. There is one other point, and that is we must do something, I believe, to prevent undue collaboration in the student body. It is now very difficult to have a question concerning laboratory work take on even a semblance of newness after the work has been gone through with by a few sets of men.

A most important thing is to reduce the number of subjects taught in the curriculum. I heartily second what Dr. Steinmetz suggests on this point; and he has also suggested the difficulty in the institutions learning to do it themselves. Each institution fears if it reduces its curriculum it will be thought to be narrowing its training, instead of which it is broadening its training. There is too much fear that we may graduate a student who will meet something in his career outside of the institution, of which he has not heard or which will seem new to him. We must eliminate that feeling. Then too there is too much of the picture-book course. There are too many problems which involve merely the substitution of definite constants in definite formulas and do not require thought on the part of the students solving them.

If the function of this Institute is to advance engineering, and I believe it is, I think there is no better thing it can do than to study the engineering training in our colleges. I do not mean to study the engineering situation as ordinary men would study it, a mere cursory examination, the interviewing of a few instructors—they have as limited view points oftentimes as other people—but I believe this American Institute of Electrical Engineers might very well make a thoroughgoing investigation of our present methods of education, and I believe if they do that and then will make recommendations for the benefit of the technical schools, that will be something of even greater benefit than the standardizing of apparatus, or the preparing of a code of ethics or a code of engineering honor, and the influence of such an investigation will start on a more fundamental plane in the improving of engineering in this country.

**F. B. Crocker:** I agree with many of the remarks that have been made, including those of Professor Clifford and the points in Dr. Steinmetz's paper, also many of those in the paper by Mr. Scott. I must, however, take exception to one statement Mr. Scott makes in regard to the so-called concentric method. He says:

> This system clashes with time-honored educational ideas, but it presents arguments which are so rational that the existing method must assume the defensive.

I think that any radically new idea must always assume the defensive, and personally I think the older method could defend itself if necessary.

The proposed method in which the descriptive, the general, and the pictorial, precede the analytical, has several objectionable features. Even assuming that it is ideal as an abstract proposition, it has certainly practical educational difficulties which are fatal. It appeals to the mind, I think, because it is attractive to the student, and therefore to one who is considering the case of the student; but the result would be to make every one an electrical engineer. Mr. Osborne tells us that 50 per cent. of those who graduate should never have entered the institution. How many more enter the institution and fail to graduate? If 50 per cent. of those who graduated should never have done so, it is fair to say that 75 per cent. of those who enter the institution should never have entered. The proposed method would graduate almost all who entered, 75 per cent. of whom should not do so. Another practical objection that no one but an educator would see is this: when a man gets to the fourth year and has had no exacting subjects—in fact, I think the plan proposes that he shall not have any very serious subjects until the fourth year, which is reserved for them—the result would be that all would reach the fourth year, and what is to be done with them then? It is a serious matter as it is now, and would be much worse with the proposed plan. We cannot exert sufficient sifting upon them in one year to make sure that we eliminate those who should not graduate and enter the profession at all. I think that these are at least two serious if not fatal objections to any such plan.

In the first, second, and third years there should be some subjects so severe, so analytical, so eliminating as not to allow men to reach the fourth year who should not, and it is still more important not to allow men to graduate to the extent of 50 per cent., or even 10 per cent. who should not do so. This seems to me an important matter, about which any one having experience should give his views, so I state what I think quite frankly, but without any personal application.

**H. W. Buck:** The two essential elements of any form of technical education are the study of the theory and the study of the practice; in other words, of the mathematical side and the physical side. The study of the mathematical element brings forth the quantitative relation existing between the various forces, movements, and dimensions in a physical phenomenon. Under the department of "practice" is developed a general conception of the physical actions and also of their commercial relations.

It is frequently argued that a student should be carefully grounded in the theory before he undertakes any practical operation or handling of apparatus involving that theory. I believe that this is not in accordance with the workings of the majority of human minds. The study of thermodynamics, for instance, takes little hold of the mind of a man who has never personally handled a steam engine. The mathematical theory of an alternating-current transformer is merely a symbolic puzzle to one who has never had personal association with the current and voltage reactions in a transformer under practical working conditions. The theory of molecular combinations in chemistry is far clearer after a man has actually made such combinations experimentally himself, and so on through many instances.

The same point is illustrated in the history of the development of science and engineering. The experimental discovery of electromagnetic phenomena by Faraday came ahead of Maxwell's theoretical co-ordination thereof. The work of Watt came ahead of that of Carnot. Newton's famous apple was obliged to fall before Newton wove his mathematical theory of gravitation around the physical phenomenon so illustrated, and so on. It all goes to show that naturally in the development of engineering science, as well as in that of the individual mind, the physical action must be clearly pictured before the theoretical treatment can be intelligently pursued.

This sequence is not usually followed in technical education. It is considered orthodox to give a student a thorough theoretical groundwork before allowing him to handle machinery in which the theory is applied, and I am inclined to think that this sequence should be reversed. A clear mental picture should be first created in the mind of the student as a foundation for the theory. The criticism applies especially in the study of pure mathematics where equations, differentiations, integrations, and other operations are studied progressively, sometimes for four or five years purely *per se* without once introducing any practical applications of the performances. As a consequence the mind of the student becomes a maze of symbolic relations and a proper conception of what mathematics is for is lost.

The highly trained theorist who is apt to hold himself aloof from the purely practical man as belonging to a superior class, should not lose sight of the fact that theory is, after all, only a means to an end, the end being the practical application of natural laws for the benefit of man. The practical man who can apply the laws of nature usefully without knowledge of pure theory, is a more useful citizen than the theorist who can not apply his knowledge practically.

In order to obtain the best results in technical education, it would seem advisable for the student of engineering first to become thoroughly familiar through practical laboratory work with the tangible and visible workings of all the principal laws of nature involved in engineering, next to co-ordinate them by quantitative theoretical study of their relations, and finally to take up their commercial application in the study of the design of practical apparatus.

**W. S. Franklin:** Sir Philip Magnus, in a recent address before the British Association, said that in his opinion education can not be called a science until we begin to study the relations between methods of teaching and the final results accomplished thereby. It seems to me that teachers are, as a body, unable to approach the questions of education scientifically according to this idea, because the results of their work are to a great extent outside of the field of their observation. It is a consequence of this fact, I think, that teachers are especially prone to the elaboration of artificial and formal criteria for judging the results of what they are attempting to do in the class-room. The tendency of teachers to become increasingly formal in their methods and in the materials of their teaching is almost beyond control by the conditions of actual life.

Calling to mind Professor Clifford's statement that education is not an exact science, I wish to affirm the point of view of Sir Philip Magnus to the effect that at present education is not even an inexact science, and I believe that this movement on the part of the American Institute of Electrical Engineers, in which practising engineers and teachers join in the discussion of electrical engineering education, signalizes the beginning of a scientific study of the subject. I think it is out of the question to expect the instructors in our technical schools to weigh the results of their work and to decide whether these results are what they are intended to be. In the institution with which I am connected, for example, we have some fifty or sixty teachers, and among that number there are four or five who have had engineering experience and who have a first hand knowledge of the demands which engineering education is intended to meet. Such a situation, which is common in all our technical schools, makes it impossible, it seems to me, to lift technical education to the plane of a science without the co-operation of engineers and teachers.

I agree entirely with Dr. Steinmetz in thinking that the hope of our technical education is in the narrowing down of our work so as to bring it within the reach of the student. I think that a great deal more stress should be laid upon the elementary sciences, physics and chemistry, and I believe that advanced technical subjects should be taught in such a way as to involve, again and again, a survey of the elementary mathematical and physical sciences which have gone before.

It would be a mistake, however, to curtail the time to be devoted to the first study of elementary physics and chemistry with the expectation that elementary knowledge could be supplied in the development of technical subjects later. The difficulty is that a technical subject, like steam engines, for example, is overloaded with detail; and a technical subject is never given with that accompaniment of simple illustrative lectures and simple laboratory work which is so necessary in the clearing up of the student's fundamental ideas.

Mr. Buck has expressed himself as to the importance of practical knowledge as a basis for theoretical study. I think I agree with Mr. Buck, although I prefer to use the expression "intimate knowledge" rather than "practical knowledge". I believe that the teaching of the physical sciences, reduced to its simplest terms, is *the transformation of intimate knowledge into general ideas*. If this be true, it is necessary to see that a young man has the intimate knowledge to begin with. For many years I have found that young men who come from the farm, or who have had experience in the shop, are very much better prepared for my work in elementary physics than young men who have been through a high school. If this kind of intimate knowledge is what Mr. Buck means by practice, I certainly agree with him, but I would hardly call it practice. The word practice, it seems to me, applies to the functions of an engineer, and what I call intimate knowledge is the knowledge a boy gets by connecting up an electric bell and playing with it until he is familiar with everything about it; or the knowledge a boy gets of hydraulics by building dams in brooks and by swimming and boating; or the knowledge a boy gets of mechanics by riding bicycles and jumping on rapidly moving cars and being nearly jerked in two. This is simple intimate knowledge of the kind that must exist before you can build up the theoretical structure which is called modern physics.

As to what Professor Crocker has said concerning the exacting character of the work in a technical school, I believe that we are now confronting a new situation in technical education. Twenty-five years ago, a man who wished to teach almost any branch of engineering had to reach up into the scientific world, as it were, and take hold of something from Rankine, or Weisbach, or Kelvin or Clausius, and drag it down into the view of his students. How otherwise could a man teach hydraulics twenty-five years ago? or dynamo theory? or the strength of materials? or the theory of the steam engine? Now, however, there is a great mass of simple technical literature exacting and precise. In the old days, mathematics was the only scientific study which could be made definite and exacting. Nowadays nearly every subject which is taught in the technical school can be made as exacting as mathematics, and, above all, the elementary sciences of physics and chemistry have been reduced to a basis which enables these sciences to be handled with an effectiveness which must soon entirely revolutionize technical education.

I believe that pure mathematics is tremendously over-emphasized at the present time in our technical schools. Every one, I think, admits that there is a very large percentage of useless developments in all of our mathematical text-books. A friend of mine, who knows his mathematics thoroughly and has no fear of it (for it is a kind of fear that holds most men in awe of mathematics), and who knows what mathematics means to the physical sciences, said to me several months ago that he believed that at least 30 per cent. of the subject-matter now included in our mathematical courses could be omitted without depriving the subject of a single element of utility for scientific and technical purposes. A mathematical friend of mine, one of the best teachers of mathematics of my acquaintance, has admitted the same in conversation with me. For my part, I believe that 30 per cent. of redundancy is a low estimate.

I think that over-emphasis on pure mathematics is to be found in nearly all of our technical schools, and I think that this over-emphasis involves not only the inclusion of a great many topics which are not useful in physical science, but I believe that it has resulted in a state of affairs which I may describe as follows: of all impersonal ideas the one most strongly imbedded in the human mind is the idea of number. Until the very recent developments of pure mathematics came about, a number always stood for some physical thing or things, beads or fish or dollars or cows, and the result is that *it is extremely easy to hoodwink a young man into the belief that he is studying about real things if his study involves arithmetic.*

I think that one of the most serious faults of our modern technical education is that it is overweighted with a great mass of numerical problems, the data of which are either entirely beyond the student's experience or with respect to the determination of which he is entirely ignorant. Such problems are, to my mind, utterly useless. They mislead young men, and also the teacher, into the belief that something is being accomplished, whereas nothing is being accomplished at all.

To my mind, nothing is more important than to associate physical ideas with mathematical operations and formulas in the work of teaching. In my class-room I have often used the following illustration: consider a wage of $2.00 per day; if you multiply this wage by 10 days you get $20.00. Now I ask my class, "how do you multiply $2.00 per day by 10 days?" but they never seem to have any notion beyond the writing of a simple tabular arrangement on the blackboard. I say, "No; you have got to work 10 days at $2.00 per day in order to multiply $2.00 per day by 10 days and get $20.00". The 10 days of labor is the physical operation that lies behind the mathematical operation, and there is scarcely a single mathematical operation in the whole range of physical science which does not have as definite a physical significance as this operation of multiplying $2.00 per day by 10 days

**L. B. Stillwell:** The answer to the question, "To what extent should the technical school devote attention to purely professional subjects?" depends upon the relative value to the graduate of professional information as contrasted with education. Undoubtedly professional information may be imparted in such a manner as to educate, but for the purpose of expressing an opinion it is, perhaps, sufficiently exact to speak of "education" and "information" not as they are inter-related but as they are contrasted. Before the question can be answered, however, it is necessary, as Mr. Scott has suggested, to define one's idea of the part which the engineer should be prepared to take in modern life.

As regards this, the conception which apparently is widely accepted, not only by preparatory and undergraduate technical students but also by many "over-practical" parents is narrow and short-sighted. The enormous advances in physical science, and in the application of physical science to modern life, are glibly asserted and reiterated, and the effects of utilization of natural laws and forces upon the economic and social structure of society are more or less appreciated. But in educating a boy for the special purpose of taking an active part in this gigantic movement, the tendency too often is to start him at the earliest possible moment in a narrow channel of thought, to narrow his intellectual horizon and make him a mere mental mechanic. This, in my opinion, is all wrong.

If graduates in engineering courses are to become generals, or even colonels, in the army of engineers it is obvious that the breadth of their training should bear some relation to the fundamental possibilities and demands of the field in which they are to labor. The engineer who desires to rise, therefore, should start, if possible, with a broad education. Truth is truth, fallacy is fallacy, and logic is logic, in any field of thought. In nine cases out of ten, mere professional information acquired in the technical school is of comparatively little value to the graduate. This is particularly true in the case of a rapidly advancing art such as electrical engineering, for the reason that a considerable part of the professional information acquired in school is out of date by the time the graduate attains a position where he has opportunity to utilize it. Practical information which he can really utilize is acquired rapidly in factory or office, in mine, mill, or laboratory. Following graduation, the work which young engineers in almost all cases are called upon to do for a number of years is highly specialized and professional information comes to him in the most effective manner. During these years, if he is working earnestly for advancement, his field of observation and thought, so far as his professional work is concerned, is necessarily limited and comparatively narrow. The opportunity for fundamental education rarely presents itself after completion of the course in the technical school, and unless prior to that time a broad foundation has been laid it never can be laid.

The ideal education of the engineer who hopes to be more than a private in the ranks is a broad one. It cannot very well be too broad. In my judgment, whenever possible, a technical course leading to a degree in engineering should follow a four years' course leading to the degree of bachelor of arts or bachelor of science. In other words, engineering courses should be regarded as professional courses and should perform the same function in the education of the engineer that the law school fulfils in equipping a graduate in the course of arts for the practice of the law.

In those cases where this is not possible, and the student finds himself necessarily limited to a course of four years in a technical school, the aim should be decidedly to educate him rather than to train him.

In my experience the following facts of observation have impressed themselves upon me:

1. American engineers to-day do not hold positions of leadership in the community to an extent commensurate with the part which engineering plays in modern life.

2. The graduates of our technical schools, while averaging well in respect to mental ability and earnestness, often lack mental perspective and are rarely capable of expressing themselves with accuracy and force.

3. The men who rise highest in the engineering profession, generally speaking, are the men of broader education.

4. Chief engineers and managers have little trouble in finding draftsmen, and less in finding competent calculators, but the demand for "all around men" always exceeds the supply.

5. The higher executive positions in administration of our great railway and industrial corporations are rarely held by engineers. In recent years undoubtedly the engineer has been making substantial progress in this direction, but usually he fails to occupy his share of the higher places in administration.

So much for personal impressions based upon observation of results. As to methods, I cannot presume to offer advice to the teaching profession. It would appear obvious, as Mr. Scott says:

> That details of method are to be determined by varying conditions and are to be adapted to the varying personal qualities of the young men.

I would particularly endorse what Mr. Steinmetz has so ably said in regard to that fault of teaching which aims at quantity and not quality. There is no good reason to believe that the ability of the human race to acquire and digest knowledge has increased abnormally during the last decade or two, but comparison of requirements in colleges and preparatory schools to-day compared with the curricula of 20 years ago, indicates that our educators are proceeding upon the theory that the average student of given age to-day is endowed with mental capacity greatly exceeding that of his father, not to mention his grandfather. The result in a great majority of cases is mental indigestion from which the student sometimes, but not always recovers, after graduation.

The cause underlying this unfortunate and very serious state of affairs is to be found probably in the ill-advised competition of schools and colleges. The school of the future is the school which will have the courage to cut out of its curriculum 25 per cent. of the studies now required for graduation and will emphasize not quantity, but quality.

**Albert F. Ganz:** Dr. Steinmetz says that:

> The least that can be expected from the college is that at the time of graduation, the student still knows all that he has been taught during his college years. To accomplish this, it is necessary to keep up the study of every subject to the end of the college course.

This seems impracticable. How are we to cut out some subjects and have less quantity, but yet to keep up every subject throughout the whole college course? I expect Dr. Steinmetz does not mean this to be taken literally. For instance, I do not suppose he thinks that the subject of chemistry should be taught to the end of the college course.

**Chas. P. Steinmetz:** I do.

**Albert F. Ganz:** Then I should very much like to know how we can cut down the course and yet keep up the study of every subject throughout the four years?

I have read Professor Karapetoff's paper carefully, and while the method has many good points, I feel very strongly that the college is the place where theory must primarily be taught; and that this theory must be supplemented by illustrations from practice by means of descriptive lectures and laboratory work.

I believe that there are four objects to be accomplished by a technical education: first, training of the mind so that it becomes an efficient machine; secondly, storing in the mind fundamental principles and facts to give to the student an understanding and a perspective of his profession; thirdly, an acquaintance with the sources of information so that the student may know where to find information; and fourthly, general culture. It seems to me that in the college we should aim to teach those things which the engineer must know, and which he cannot readily obtain in practice, nor from general reading. As an example, the mathematical theory of alternating currents should be taught in the school, because in practice the engineer would not learn that theory nor would he readily be able to get this from his own reading. I also believe that the laboratory experiments should be designed primarily so as to impress upon the students the main fundamental principles, not designed to imitate the tests that have to be performed on the test floor of a large manufacturing establishment. I do not believe that the latter is possible in a college laboratory. That is an example of the kind of information which the engineer can get from practice. I always advise our graduating students to spend one or two years after graduation in the shops of one of the manufacturing companies. Fortunately for the technical schools, the large electrical companies have established apprenticeship courses where it is possible for the student, after graduation, to become familiar with large machines under commercial conditions.

I should like to have the Educational Committee suggest what cultural subjects should be included in the curriculum, and how much time should be devoted to them. At the Stevens Institute we include in our curriculum courses in business engineering, English, German, and some lectures on patent law and on contract law, and we hope to include more cultural subjects.

Mr. Buck speaks of teaching the design of practical apparatus. I question whether in a technical school it is possible to teach practical design to any considerable extent. I rather agree with Dr. Steinmetz, that it is better to analyze existing apparatus than to attempt to make actual designs.

**J. G. White:** There seems to be a virtual unanimity of opinion, that the aim of the college education for engineers should be to build up a foundation or groundwork based on the fundamental subjects of which the engineer should have knowledge, rather than to give him specific information. I fully agree as to the thorough wisdom of this. Specific information can be readily acquired after leaving college, whether it be with one of the large electrical companies, or in a consulting engineer's office, or out in the field in erecting machinery, or elsewhere. The fundamentals, such as a good general knowledge of mathematics, and a thorough knowledge of physics and chemistry, both of which I consider extremely important, cannot readily be acquired in the field; that is one of the reasons why they should be acquired during the college courses. The subjects that are useful primarily because they are a benefit to one's general culture are less readily acquired in practice, partly because the facilities are not so conveniently at hand and partly because one is likely to be absorbed in the performance of daily routine duties, so that it is difficult to find opportunity to put thorough study on subjects not requiring attention by reason of such routine duty.

So far as the general usefulness of different subjects is concerned, it seems to me that, as intimated in the previous statement, there should be a thorough and broad training in mathematics, in chemistry, and in physics, and I believe with Mr. Steinmetz that all three of these can be carried through the college course. No one should specifically study calculus during the entire course, nor specifically study elementary chemistry during the entire course; but in the later studies, dynamo design, for example, enough calculus can be used advantageously to keep one from forgetting the general principles of calculus, and so one can, in the study of electrochemistry, in connection with experiments with storage batteries, or in other like ways, have enough use for chemistry to prevent one forgetting the elementary chemistry learned in the freshman year. In similar ways, if a course is laid out correctly, one can be kept from forgetting other subjects which have gone before. In addition to English, which I am glad to see is being followed up more consistently and persistently, one of the subjects which I perhaps am inclined unduly to value is the study of Spanish as compared with other language studies. It seems to me that Spanish has practically as much educational value, and almost as much value as a culture subject, though perhaps not quite so much as French or German; but it is so much more likely to be of use in practical life after graduation, that I strongly favor the average engineering student studying Spanish, if he possibly has the opportunity of doing so. If he can study one other language, Spanish as a second is distinctly desirable. It is a comparatively easy language to learn.

Another suggestion which perhaps our friend from Stevens may like to hear in plain English is that ordinarily I believe the college professor is too much inclined to rely on lectures and too little inclined to depend on well-worked out, well-planned text-books which some other professors, or groups of professors, have written. The lecture room is of great value in physics, chemistry, and in electrical engineering, for illuminating and illustrating fundamental principles, but these fundamental principles should be put before the student in such shape that he has something to study and restudy, can have impressed on his memory. His time should not be wasted by making a lot of notes and going through the mechanical operation of copying them, when, after he has them copied, he probably has no adequate understanding of the subject. Another beneficial trend of many general educational courses is toward doing away with too great freedom in elective studies. About the time I left college there seemed to be a great tendency toward putting all students entirely on the elective system, leaving nothing on the required curriculum. There seems to be a drifting back to the good old-fashioned days of mapping out a set course for young men, and I think that practice can be advantageously followed further than it has been. It seems to me that a group of professors in consultation with other officers of an educational institution, and with the advice of graduates and trustees, can decide to better advantage what the ordinary engineering student of 17 or 18 years of age should study, than can the young man himself. That is surely true of technical courses, and I should be glad to see more text-books, fewer elective studies, and the required studies more confined to general principles and foundation work and less given to doling out general information.

**W. E. S. Temple:** There is a noticeable tendency on the part of those who have been out of school for ten or twenty years to overestimate the amount of preparation which the technical graduate should have. In considering the subject, it is necessary to try to state what the object of an engineering education is; we can then see better what it should consist of. It is admittedly impossible for a man still in school to know just what line of work he may be best suited for, yet this is the age of specialists in electrical engineering, as well as in other professions and on this account the object of the technical training should be to provide the man with the means to receive the best development in that special kind of work into which he may be placed after graduation.

The education must therefor consist in grounding the man in principles and general applications. This will give him the tools with which to develop himself when he becomes enrolled in the school of experience. A great many rules and formulas have been suggested, indicating how best to accomplish the laying of this general foundation for development, but rules and formulas cannot be applied here any more than they can be to regulating the politics of New York or of Philadelphia. We must set before ourselves a certain aim, and keep examining ourselves as to methods, taking account of stock as it were, and make sure that we are getting the best results possible.

Another thing that should be accomplished in addition to getting a thorough foundation in technical principles, is lifting the man's ideals high as to his future position as a man of affairs. There is no reason in the world why the engineer, who is responsible for so large a proportion of the wealth and resources of this country, should not have more control over them, and more profit from them.

The quality of the work done by a student actually depends upon himself as much as it does upon his teachers, and therefore the entrance requirements deserve as much attention as does the laying out of the work after he begins his technical training. To outline the actual subjects which should be taught is not difficult. There are a number of lists which are in use, some preferable to others, but all of them good, for they are producing favorable results. It seems to me there should be more of those subjects which develop the man's power to reason along lines related to engineering, and less of those which fill his mind with a useless store of technical data that can be found in handbooks. As to the suggestion in Dr. Steinmetz' paper that physiography, metereology etc., be taught; why not a course in architecture and perhaps practical politics too? These are really as much related to the subject of engineering, and are as broadening, as the subjects he refers to, perhaps more broadening. It seems to me that specializing is not preparing the student for the best development, and a too great indulgence in it prevents the college from doing the greatest good for its men. I am referring, of course, to the undergraduate students.

One of the vital features in the education of the engineering student, it seems to me, is the method followed in taking up the work. Mr. White referred to the matter of lectures; I do not think that any hard and fast rule can be laid down for this. The rapid progress now being made in electrical engineering demands that some of the subjects relating to the applications of electricity be taken up in lectures. I know of no text-books in existence at present which are suitable for this part of the work. The elementary subjects, and the general applications of electricity should, in my opinion, be invariably taught by the use of carefully selected text-books concurrent with the solution, by the student, of various kinds of engineering problems. These problems should involve not only the new ideas and principles as they are taken up, but they should also depend upon subjects already gone over in earlier parts of the course.

The classes should be subdivided in sections of about ten men each for all recitation work, thereby insuring more nearly individual instruction, and making it possible for each man's needs to receive attention. The greatest stress should be laid upon promptness and accuracy and general attention to work. The student should be penalized for absence from classes, or for tardiness in doing the work assigned to him, even though he may do that work in a most satisfactory manner from every other standpoint.

Laboratory work should be individual as far as possible. If the men work in groups of two or three or more, upon one test, it is not possible to make sure that all of them get all the benefit which they should have from the work. The inferior man will allow the better man to do it all, nearly every time. The only sure cure for this is to make each man work alone. This method is, no doubt, more expensive, but if the thing is worth doing at all, it is worth doing well. Furthermore, the best results will be obtained if each man is obliged to set up his own apparatus, and wire up his own test. If he is a particularly good man, it is not a bad idea, occasionally, to put the machine in trouble in some way or other; this method will require more time for each test, but quantity is not what we are aiming at; it is quality we are after, and this method is bound to produce a far higher grade of work, and to develop in a much greater degree, the man's thinking, and reasoning powers.

The method of concentric instruction has been very adversely criticised, and it seems scarcely necessary to speak of it any further. The idea, if applied to one subdivision of one of the subjects of electrical engineering, might be good. It is however utterly impossible, as has already been pointed out, to go into details of construction and operation of machinery, particularly electrical machinery, without having the theory to resort to for explaining the why and wherefore. As I understand it, this method proposes to complete all the practical considerations first, leaving the theoretical features until last. The result of this would be that in going over the practical parts with no theoretical preparation the man would perforce become a confirmed empiricist, and when he came to the theory later on, he would be perfectly satisfied to omit it entirely, or at least he would fail to give it the proper attention. The summary of the paper shows a great many things which this concentric method will accomplish; it will produce a somewhat finished artisan at the end of the first year, a little better artisan at the end of the second year, etc. It reminds me of a machine that will do a dozen different things, but none of them properly.

**Louis A. Ferguson:** The great value of an engineering education to a young man about to start in his life's work lies not so much in the actual knowledge he may bring with him, but in the training which he has received. The accumulation of a mass of data is not the important thing, but the reasoning power which he has acquired is what will serve him in good stead in after life. The technical training of our engineering schools develops an analytical turn of mind and teaches the young man to differentiate between right and wrong, promotes sound judgment, which, after all, with initiative and optimism, is one of the great factors in producing the successful man in any walk of life.

It is a mistake, as Dr. Steinmetz has clearly pointed out, to try to jam the maximum amount of information into the student in one year, only to be forgotten the next. Premium should be placed upon the development of reasoning power rather than the mere memory of the student, and any subjects that he must know in his practice after graduation should be kept constantly before him throughout the entire course, so that he may carry his knowledge, once acquired, with him into the world.

There is a tendency in some educational institutions to a practice which I think is not conducive to the best results. I refer to what might be called "inbreeding", that is, the general employment of graduates of a given technical college as teachers and professors in that college. This promotes narrowness of view among the students, mental fatigue among the teachers, resulting in the decline of the educative ability of the institution. The faculty of an engineering college should be made up of men graduated from as wide a range of colleges as possible. Eastern colleges should have some professors who have been trained in the West and South, and western colleges should have professors who have been trained in eastern institutions, so as to give as broad a character to the education as possible, and to keep alive in the faculty itself real interest in its work.

We find in the management of industrial corporations that the best results are obtained by following this principle in the employment of engineers. The very college patriotism which exists in the heart of every true American will prompt him to try to equal in efficiency his fellow engineer from another institution, and this rivalry, which must be friendly to accomplish the desired result, is bound to make finally for the interest of the corporation.

Professors and teachers are not as a rule sufficiently encouraged by their college management to come in contact with the practical side of engineering, or the work accomplished in other similar institutions, as they might be were they given the opportunity to mingle more with practising engineers and industrial managers and by travel in this and other countries. They are, as a rule, forced to gather their information by reading and study which is less satisfactory than actual contact and observation.

Why, if the industrial corporations find it profitable to send their engineers and managers to other parts of this country and Europe to study conditions and make comparisons, should not the technical colleges and institutions find it equally so to do the same with their teaching staff?

The scope of the course of electrical engineering in some institutions, it seems to me, is too narrow. The graduate electrical engineer, for some reason, is considered by some employers to be devoid of ability to discuss anything but electricity, and his opinion on other matters is discounted and oftentimes very unfairly to him. This is unfortunate, as there is probably no branch of engineering which requires so general a knowledge to be successful as that of electrical engineering.

The course in electrical engineering should include the fundamental principles of mechanical engineering and civil engineering, chemistry and hydraulics, building construction and general business law, as well as theoretical and applied electricity. The student should be impressed with the fact that a general fundamental knowledge of the branches of engineering other than pure electrical is paramount to ultimate success in electrical engineering, if by that we mean obtaining a position whereby one is given the responsibility of conducting large engineering undertakings, or the management of large industrial operations.

**Samuel Sheldon:** That educational institutions are unable to obtain the best type of instructors because of the low compensation which they offer is recognized by professors, by those who wish to be professors, by engineers, and by the presidents and trustees of these institutions. The mere announcement of the fact will not better the conditions. Much could be accomplished by a co-ordinated movement on the part of all technical institutions to increase the tuitions from students who are able to pay, leaving the funds which are derived from philanthropists to be distributed, so far as they last, in defraying the expenses of worthy and selected students. In reference to quality, as distinguished from quantity, the Educational Committee of the Institute would perform a useful service if it should bring about a curtailment of the matter which is at present presented in connection with the instruction in each and every subject in existing courses. Such curtailment, in view of the fact that courses will doubtless be limited to four years for some time to come, would result in a saving of time which could be utilized for needed culture subjects, and for the amelioration of existing conditions towards which the so-called concentric method of education is directed.

In reference to Mr. Scott's paper, the extracts from the Institute papers are on the whole so general as to be of little value to one engaged in laying out a curriculum. One, however, and that is from the paper presented by Professor Karapetoff, is very definite, and the original is accompanied by a specific schedule for each year. The advantages which it is claimed would result from the use of this concentric method should be obtained, if possible, but it does not seem necessary to make use of such radical means as are outlined in that schedule. Associated with it are two marked disadvantages: first, the hiatus in the pursuit of mathematical studies must inevitably result in educational inefficiency; secondly, training in physics, which is an absolutely essential prerequisite for any serious engineering study, is deferred to too late a period.

Tests of the absorption power of an average freshman indicate that a cyclopedic view of all engineering could be profitably given during the freshman year without consuming more time than could be obtained from a judicious curtailment of the freshman schedule, as at present existing in most institutions. Experimental electrical engineering is also required early in the concentric schedule. Physical laboratory work could readily be so laid out as to constitute a course in experimental electrical engineering.

**P. H. Thomas:** In its broadest sense, engineering is a method, not a profession. By this view, "engineering" is the application to new problems, through the methods of logic, such as mathematics, the knowledge of experiment, and experience. This method is applicable to many branches of activity not included in a narrow definition of engineering. There is every reason why the banking, trading, and selling work of the country should be carried on by men trained as are mechanical, electrical, or civil engineers, but in a different subject-matter. In fact, this state of affairs seems to be rapidly approaching.

Although the object of technical education must be, strictly speaking, to perfect a man as an engineer, expediency requires that at the same time he must receive such culture training as he is to get at all during the same period. The man should by no means be sacrificed to the engineer. Fortunately, such culture training as is appropriate will usually benefit the engineer. The factors of greatest importance underlying successful engineering are perhaps the following:

1. A thorough appreciative knowledge of the laws of nature and of the properties of materials. These laws and properties, as used in engineering, are simple and relatively few.

2. Familiarity with the mathematical and other logical processes by which the fundamental laws are to be applied to special cases and results numerically computed. Here self-confidence and the power of applying knowledge are of the greatest importance. It is here that many graduates are lacking. This section must be construed very broadly to include the underlying principles of all types of machines.

3. Familiarity with the results of experience; what has actually been accomplished in the past and just how. This is of the greatest importance and is, further, the basis of the great mass of actual engineering work done. The results of past work are found partly in the general practices of the community, partly in books and periodicals, and partly in the records of individuals of experience. Here should be included, at least for the more ambitious engineers, a knowledge of the more important experimental work done and the new methods and apparatus proposed by inventors.

4. Acquaintance with the actual methods, standards, practices and engineering terms in vogue in any particular community. These may be different in different places; but one engineer can not work with another without this acquaintance.

Over and above these four conditions the effectiveness of an engineer depends, of course, on his personality, but this is not properly a matter of education.

The actual period of an engineer's development in which he may be said to be receiving his education is perhaps ten to fifteen years, beginning with his technical school work. Of this period, four years are usually devoted to school work, a good proportion. Here comes the practical question to be considered: to what shall these four years be devoted? In my opinion to the first and second and to the more fundamental facts in the third division of engineering knowledge just given, and as well to some culture studies.

The study of natural laws, of the characteristics of materials and all mathematical work is best done in class work. Here should be included the laws of force and motion, of heat and sound and electricity; such subjects as mechanism and mechanics and thermodynamics. Also, for electrical engineers, such information as the laws of parallel circuits, induction, resonance, wave motion, the natural characteristics of different types of electrical apparatus intrinsically, as transformers, series and shunt motors; also principles of compounding, field distortion, etc., induction motors, synchronous machines, etc. But not such subjects as commercial designs or designing of apparatus, constants of design, the relative merits of different makes, physical description, compilations of actual costs, efficiencies, and other data of actual plants, nor much study of actual installations. These all tend to distract and to lessen interest in the more fundamental things that cannot be learned later.

The subject-matter here assigned to the school years is in the long run of the greatest importance and cannot be well gotten later. The other subject-matter covered in the four divisions of engineering knowledge is readily acquired in actual practical work, but only with the greatest difficulty in the class room, and then imperfectly.

The engineer must specialize, even within the divisions of civil, mechanical, electrical, etc. The specialization should not however prevent an appreciative knowledge of all other important branches. As Dr. Steinmetz has said a good descriptive short course can give a group of fundamental phenomena, and the essential or individual character of such a branch in a way, that will permit a real appreciation of its significance. The influence of these related branch studies is tremendously broadening.

It is not for the practising engineer to specify in detail the course of the technical school, this is for the specialist in education, the professor; but the engineer may suggest a measure, by which a course may be judged. The following is an example. Does the course give:

1. A clear, thorough, appreciative knowledge of the natural laws used in engineering work. Also, a good knowledge of the properties of materials.

2. A clear, working knowledge of the mathematical methods, formulas and other logical processes by which the fundamental laws can be applied to individual cases and numerical computation made. Also, a familiarity with the characteristics of the sorts of apparatus commonly used (not commercial types) in electrical work—transformers, motors, generators. Is the student's knowledge and training of such a character that he can personally use his data and formulas and have confidence that he is right?

3. Has the graduate enough general culture to feel the equal of and at home with the other men (not necessarily engineers) that he meets?

4. Has the matter been so presented as to be grasped in the easiest and most permanent manner? Has the interest been kept up and the meaning of the work made clear by some view of the practical field into which the student is to pass?

**W. L. Robb:** A matter that has an important bearing on the curriculum of engineering schools, but not mentioned this evening, is the relative lack of preparation of men who enter these schools. It is a notorious fact that the great majority of men who enter technical schools have not completed a high-school course. Men generally enter the technical schools at least a year before graduation from the high schools. Virtually all the technical schools have lower entrance requirements than the colleges. Where the requirements are nominally high, the examination in the non-mathematical subjects is relatively easy, the examination in mathematics being the real basis of entrance. The majority of men entering medical and law schools at the present time are college graduates, much more highly trained than the men who enter the technical schools. As a result, a large part of the first two years in the technical schools has to be given, not strictly to engineering subjects but to general mental training. Under the present condition of things, culture subjects have a place in a technical school, but I believe they only have a transient place. I do not think that a course in English or history or political economy has any more place in a technical school than in a medical or a law school. We should see that the entrance requirements of the technical schools are brought up at least to the entrance requirements of the colleges.

With entrance conditions as they are at present, the first two years of a course should be mainly given up to the study of mathematics, chemistry, physics, English, and one other language, preferably a language that is inflected. I do not think it makes much difference whether the language is Spanish, French, German, Latin, or Greek. As far as the commercial usefulness of the language is concerned, I believe thirty days spent in a foreign country will prove more valuable than two years' study of the language in a school.

The third year of the course should be devoted to mechanics and the fundamental principles of civil, electrical, and mechanical (including steam) engineering. There should not be much, if any, difference in the way these subjects are taught in the various engineering courses.

The fourth year I would devote mainly to highly specialized subjects in that branch of engineering in which the student elected to take his degree. The student should have the privilege of specializing along some desired line before graduation.

I do not think we should have in engineering schools courses specially devoted to business methods, depreciation, operating costs, and similar subjects; but I think any man capable of being at the head of an engineering department should infuse these subjects into the minds of his students in connection with the regular work.

**C. O. Mailloux:** I have, presumably, at the present time, all of the qualifications for speaking on this subject, since I am a practising engineer, and, at the same time, happen to be an "amateur" teacher in one university, and an "amateur" student in another. The complete period of instruction of an engineer, which Mr. Thomas speaks of as being fifteen years, is too short for the man who believes in progress. I find that it can be profitably extended to at least twice that time.

I agree fully with Mr. Stillwell. His discussion states the facts, from the standpoint of the enlightened progressive engineer, very well indeed. I endorse his plea for broader education, now, just as I did at the Great Barrington meeting. Like him, I have found, and I so stated at Great Barrington, that, oftentimes, the man of broad general culture is of greater utility, and makes more rapid progress, than the man who specializes too soon. I also agree, with him, that there is an abundant supply of the mediocre man, but a scarcity of the man able to do original work. In looking for the causes, we find that there are many, and in looking for the remedies, we find that they are diverse. Yet, after all, we find that the general principles have already been reviewed in previous discussions; and I noted, with some interest, as the discussion progressed, and as I classified the points covered, that most of the formulated statements regarding the requirements of technical education have been given already, in previous discussions before the Institute, particularly in the papers of Professor Esty and of Dr. Sheldon. Professor Esty gave, in his paper, a resume of the requirements, so well, that, even after the discussion here tonight, we do not find that we can improve much upon them. Dr. Sheldon's discussion differs from Professor Esty's only in so far as it goes further, or attempts more. It aims to build a "pyramid of knowledge" of greater height, and therefore postulates a broader base. I have already spoken of that pyramid fully, in my discussion, at the Great Barrington meeting; and I need only add now that my views have not changed in regard to it. In that discussion, you will also find a reference to the subject of "mathematical dyspepsia" which, I think, is still pertinent. There is nothing which causes so much contention and dissatisfaction among teachers, students, and engineers, as the teaching of mathematics. A great deal of effort has been devoted to finding better methods of teaching mathematics. I am often questioned by both teachers and students of engineering about that subject. I expressed my views fully on that subject at the Great Barrington meeting. I also made some reference to the views of Dr. John Perry, who has some perhaps radical, but very good, ideas on the subject. I am glad to say now, that the ideas of Dr. Perry have actually led, since then, to wholesome reforms in methods of teaching mathematics in England.

My own view about engineering education is that we should attempt much less, and yet, attempt much more. We should attempt less in not trying to cover so much ground and so many details, but we should attempt more in trying to cover fundamental ideas and principles more thoroughly. I often find that students are bewildered and discouraged by the size of the text-books given them. If the text-books were smaller, or less terse or rigorous, if they covered fewer points and covered them more thoroughly, they might, perhaps, be less imposing, but they would be more "effective" as repertoires of knowledge for engineering students who do not expect to become teachers.

On the subject of lectures, as distinguished from text-books, I may say that my experience, both as a teacher and as a student, leads me to believe that the ideal method is to combine the best *features* of both. I believe in a method in which the student receives guidance and instruction primarily, and whenever possible, from lectures, but works in connection with text-books, or, in the absence of text-books, (and, *preferably*, in all cases, when it can be done), with a carefully prepared up-to-date, and not too much condensed, syllabus. My own method in teaching, is to ask the student to take as few notes as possible. I try to give them ample ready-made notes of all the principal points and all the main details of the discussion; and I also refer them to all books which can be of assistance to them by throwing more light on the subject. I know, by personal experience, how often one makes errors in taking down notes and how difficult it is to correct notes taken down wrongly.

In regard to the teaching of mathematics, pure and applied, there is danger that, while trying to cover the moderate wants of one class of men, we may neglect to cover the higher wants and aspirations of another class. We must consider the kind of material that we work with, and the kind of men that we expect to turn out. It all depends on how high the pyramid of knowledge is to be built. If we seek merely to turn out mediocre or average men, we can get along with relatively little training; but if we wish to turn out men who are to be colonels or brigadier generals in the profession, then we must place at their disposal the facilities whereby they may acquire that higher training which they should have. It may be that we cannot do both of these things in the same class, or even in the same school. At this point let us say a word about the distinction between theory and practice. I think that too much emphasis is laid upon the importance of the student being brought into physical contact with those facts which he can gather with his eyes and hands. Any person who has given the slightest thought to education knows that it is not so much the facts which are discovered by the eyes and hands that are important, as it is those which are discovered by the mind. There are certain " facts " which are more important than even the individual, oftentimes detached, physical facts, gathered by the hand or the eye; and those higher facts are called principles. These are usually the facts which furnish the key to whole treasures of facts. Thus, while it is true, as Mr. Buck said, that Watt came before Carnot, yet, it is also true, that Carnot came before Corliss. We also know that Hertz came before Marconi, just as Maxwell and Faraday came before Hertz. There is an important distinction to be made between the use of mathematics as a means of technical training and as a means of technical research. There is a legitimate use for both. We may possibly have done too much in the way of using mathematics purely as a means of training for engineering students. We should, in the training of engineers, perhaps, use more applied mathematics and less pure mathematics. But here, again, we should bear in mind the needs of the higher technical science and look to the great engineers to see what they have done as the result of specializing and higher training. The distinction of a school is due partly to the distinction attained by the great men who received their training at that school, and partly to the distinction of its teachers. It is worth while and is inspiring to look at some of the great achievements in our profession, and to see the means whereby they have been attained. Some of these things are of the greatest significance, and they point to a moral in regard to methods of teaching and the way it should be directed. Two of the greatest achievements in electrical engineering, in my opinion, have resulted from the solution of differential equations. They are feats of applied mathematics. The first of these achievements was made when that great electrical engineer, Lord Kelvin, solved the differential equation since known as the "telegrapher's equation", and, in doing so, predicted all that it was essential for us to know, and foretold the facts and the practical essential conditions that were afterwards observed, in regard to submarine telegraphy. That solution was the key to submarine telegraphy. The second achievement was another solution, a far more complete solution, of that same differential equation, by Dr. Pupin; and this latter solution, which turned out to be the first general solution, has done almost as much for telephony, as the solution of Lord Kelvin had done previously for telegraphy. These two cases show that, when the greatest results in electrical engineering are the goal, even the most complete equipment, intellectual or technical, is not too great. As to what constitutes the modicum of requirements which a student of engineering should satisfy, my opinion is that these requirements include three or four principal branches. I might say that, of physics—the fundamental physics of energy in all its forms and manifestations—the student cannot have too much. He might have too much physics if he is led into the by-paths of physical research too early, but of fundamental physics he cannot have too much. If we include mechanics and chemistry in physics, then we may say that the principal part of the engineer's education should be physics. Let us say, then, physics, mechanics, and chemistry; and let us not forget mathematics; but there should not be so much pure mathematics as applied mathematics; there should be just enough pure mathematics to enable the student to get along in applied mathematics. I believe strongly in analytical mechanics and even in some mathematical physics, both of which are applied mathematics, with physics. In a word, I believe in plenty of fundamental physics, taught both ways, experimentally, and also by mathematical methods. Too much time is spent in teaching mathematical abstractions which the students cannot possibly remember. The pure mathematics should include the essentials and fundamentals of algebra, geometry, trigonometry, and the calculus, leaving the refinements thereof for later attention on the part of the student, after he has learned to appreciate their value. I cannot quite agree with Professor Robb as to the transient features of culture in the curriculum. He contradicts that opinion himself, to some extent, when he says that facilities should be given to students for specializing, since specializing is a means of broadening the student's culture. One of the sad facts which should be realized more than it is, is the want of general culture in the engineering profession. Mr. Stillwell has brought that out clearly. I believe, with Professor Robb, that one of the most important difficulties lies in the fact that the students are placed in contact with the engineering part of their education too early, before they have had the necessary amount of preparation, or even, I might say, of intellectual growth and development. Perhaps the solution of the entire problem will be to increase the requirements in regard to the preparatory studies pursued and to apply an inferior limit to the age at which students are allowed to enter the polytechnical courses. We should not expect to make children engineers, any more than to make them doctors or lawyers. One remark of practical importance is that made by Professor Clifford, in reference to a committee of engineers acting in consultation with the faculty or the heads of the departments. There may be a great deal of good there; but there is also a possibility of harm. I know, from having seen men teach, that there is as much difference in teachers as there is in pupils and I know also, from having attended lectures by "outside" men, so-called, that some of these lectures are apt to be quite as bad as they are apt to be good. I mean that the practical man is "fit" as a teacher only when he has retained such contact with the theoretical side of his profession that he can still be able to lead instead of mislead the student, when he presents his subject to them. I have seen cases of that "misleading" kind which brought home to me the lesson that he who undertakes to teach practice, must know thoroughly the theoretical part as well as the practical part. The man who undertakes to teach theory alone may get along with little, if any, knowledge of practice at all: but the man who undertakes to teach practice must know both the practice and the theory.

The idea of segregation, which was referred to, seems an excellent one, and it may be that the future will lead to it by a natural process of evolution. There has been some suggestion made, in fact, of technical schools which would be devoted to advanced technical teaching, either by taking men who meet higher entrance requirements, or by lengthening the course, In that way, by having the high grade men in a different class or school, we would be able to train high grade men so as to make them attain the highest efficiency.

**Philip Torchio:** Neglecting the all-important questions of individual talent, commercial acumen, and executive ability, which are mainly acquisitions by birth and surroundings, we may classify the students of engineering into two classes: one pursuing a college course to master the technical engineering knowledge, aiming to apply it directly in the conception, design, and carrying out of original engineering works; the other acquiring that knowledge as a means of securing a better class of employment or as a stepping-stone to commercial, industrial, or financial pursuits. Theoretically, the education of these two classes of students should be essentially different; the first requiring for his career a greater equipment of mathematical and theoretical training than the latter, for whom the practical side is of much greater importance. The measure of professional success in their respective fields of activity is in one case the amount of retainer and consultation fees, and, incidentally, social prominence; in the other it is the salary received or the increment profit secured by the commercial exploitation of any specific independent industry. If the two classes of students must be put through the same courses, I think that we would come to the conclusions reached by Professor Karapetoff, as a matter of expediency if not as a matter of choice. Professor Karapetoff's method will appeal most to the managers of industrial corporations and the majority of employers of engineering skill. It is a striking fact that most of the leading positions in industrial enterprises are to-day not filled by technical graduates. A few years ago about forty high officials of a large manufacturing corporation were seated at a dinner, and among all of them none was found to be a college graduate. As this corporation is considered here and abroad a model organization, such condition of affairs should command the earnest consideration of educators.

Conditions will change, I might say are changing now, but the progress is slow. We must, therefore, place our aims high, but not forget the local and present conditions, demanding highly specialized and practical knowledge. Our great centralization of industrial interests makes still more necessary a greater refinement of specialization than exists abroad. We may all deeply regret this narrow-gauge education, but we are leading the world into this condition. The great number of young electrical engineers are affected by these conditions. On the other hand, this very high degree of progress and specialization. combined with the importance and magnitude of the engineering work done in this country, creates a demand for exceptionally high engineering standards on the part of the relatively few leading men who pilot the heavy engineering and scientific work of the country. These different requirements make the problem of technical education more difficult. Now, if we must specialize, and we have the resources for doing it, why should not the colleges for electrical engineers also specialize, and equip themselves, some to turn out practical engineers fitted to fulfil the positions in industrial enterprises, and some to turn out electrical engineers with a much broader theoretical and scientific education, befitting the requirements of the broad engineering profession. The only obstacle that I can see would be an ill-placed jealousy among the different colleges.

I have no doubt that eventually we shall come to such results, as present indications point clearly that way. The majority of colleges will continue to bring into greater prominence the immediate practical applications of each engineering branch. On the other hand, a few other colleges more favorably situated will develop along more scientific lines, aiming to give a broad engineering education, possibly branching out into specialized electrical studies only in the last one or two years of the course.

I have the privilege of giving the experience of the Royal Polytechnic of Milan, Italy, which was started forty years ago along the lines of broad engineering education I have just referred to. About twenty years ago a course of electrical engineering was established through the private endowment of Carlo Erba, as an adjunct to the Polytechnic. The Polytechnic is a government institution but created mainly through the efforts of the late Professor Brioschi, a man of rare talent and ability, who imparted to the organization a good deal of his strong personality. The essential requisites for admission are the government certificate either of an eight-year preparatory course in a lyceum, in which classical studies prevail, or a seven-year preparatory course in a technical institute, where physical and mathematical studies and modern languages predominate. The average age of a freshman class at admission to college is about nineteen years.

The engineering course consists of five years, the first two being preparatory to all engineering courses, and the last three being sectionalized in three classes of civil, mechanical, and electrical engineers. The first two years cover a thorough study of the calculus and higher algebra, analytic, descriptive, and projective geometry, general chemistry, mineralogy, physics, drawing, etc. In the next two years the mechanical and electrical engineers jointly follow, theoretically and experimentally, the studies of mathematical mechanics and applied mechanics, theory and design of steam, gas, and water power prime movers; design and calculations of parts of machines, resistances of materials and general construction, hydraulics, organic and inorganic chemistry, surveying, descriptive study of industrial plants, such as foundry and working of metals, cotton, silk and flour mills, etc.; technology of electricity, heating and ventilating, construction and operation of steam railways, etc.

In the last year the electrical engineers in common with the mechanical engineers complete the last courses in mechanics, hydraulics, mining, technologies, etc., and make two theses consisting of comprehensive detail drawings of a prime mover and plans of an industrial plant, and follow separately the course of dynamo and transformer design and operation, industrial applications of electricity, theory of electrical measurements and laboratory work.

The total lecture, laboratory, and draughting room work consists of 48 hours a week, 8 hours per day, approximately evenly divided, half for lectures and half for laboratory, draughting, etc. During the last years of instruction, the students under the direction of the professors carry out comprehensive efficiency tests of power plants and other industrial tests, measurements, and surveys, and make frequent visits to industrial plants throughout the country and to expositions, whenever feasible. The school discipline is very strict, and willingness and ability to do intense and sustained work is a requisite for remaining in the Institute. The teaching personnel for the theoretical subjects is made up of regular professors, while for almost all the engineering subjects the personnel consists of engineers, who, besides the educational work, have a large consulting engineering practice. This arrangement has worked out successfully in Milan, the main reason perhaps being the fact that Milan is the largest industrial center of the kingdom.

From his long experience with the polytechnic, Professor Brioschi has found that by an overwhelming majority the most successful careers are made by engineers whose early training and mind discipline had been along lines of broad classical and liberal education rather than those who in their early training had had a preponderance of practical studies like physics, mathematics, and modern languages. These results are rather striking, and, one would almost say, unexpected.

While realizing the difficulties of establishing comparisons and drawing conclusions for conditions vastly different, I do, however, believe that in this moment, when people under the pressure of a strenuous life are clamoring for simplified spelling, practical education, and other short-cut schemes, we owe it to our profession to place our aims at a high level; it is due to the intellectual standards of our leaders and the importance of our work in the community, and we should back up our position with doing all that is in our power to promote and advocate for this country, alongside but distinct from the highly specialized engineering schools, the evolution of a few centers of learning where the most liberal engineering education can be secured by those who by intellect, aspirations, and other favorable circumstances can afford to undergo a broader preparatory work and possibly a longer term at the college.

These centers, by attracting the best talent of the country to their educational staff, would indirectly benefit the other colleges by raising the standard of the whole profession, and would be a nucleus for that free intellectual and scientific activity which is the guiding spirit of the progress of this country.

**President Stott:** Thinking over this subject and listening to the discussion impels me to emphasize one or two points. The professors have asked us to be specific in criticism. The discussion to-night might be summed up by saying that there is a lack of general education of the freshman entering college. What is that caused by? The smattering of everything he gets in primary and high schools, a little of this and that, nothing taught thoroughly. The remedy for that is for our technical schools to raise the standard of their entrance examinations. If that be done, the other schools will be forced to raise their standards to meet it. The discussion seems to lean distinctly toward the point that engineering schools should teach fundamental principles and not engineering practice. I do not believe degrees should be granted until a man has been out of college for at least five years. In Great Britain doctors do not get their M.D. degree until they have been out of college and practicing for a number of years. I believe no one should receive a degree of mechanical or electrical engineer until he has had the practical training to make him worthy of such a degree. The weeding out process, which is inevitable at some stage, is a very hard problem; there are many reasons, financial and otherwise, why it should be almost impossible for a technical school to weed out students who, whilst qualified as students, are not likely to become engineers. If the degree in engineering were to be conferred only upon proof of work done, say five years after graduation, the stigma of the weeding out process would be taken away from the college; and when a man received his final degree in engineering, it would really mean that he was qualified to state that not only had he the necessary theoretical knowledge, but that he had also survived the refining process which sifts out 50 per cent. of our graduates in the first five years, leaving only those who are likely to become successful engineers.

**Chas. P. Steinmetz:** It appears to me that the question, how to get a thorough understanding of the fundamental principles, is answered in my paper. Drop out a sufficiently large part of the matter which the college now attempts to teach, so as to find time to improve the quality of the rest by thoroughly teaching it; that is, going over the subject over and over again, approaching it from different view points. After all, a clear and thorough understanding of a subject is gained only by looking at it from every possible point of view. For instance, the induction motor is not understood properly by considering it as a short-circuited armature revolving in a rotating field; it is not understood by considering it as an armature acted upon by a system of quadrature magnetic fields; it is not understood as a derivation of the direct-current shunt motor, combined with the transformer action transferring power to the rotor instead of leading it in by commutator and brushes; nor is it understood by considering it as an electric circuit revolving in an alternating magnetic field. It has to be looked at from all these view points before it can be understood. There is no time for this in the present college course. From my experience with very many college graduates, Americans as well as the product of foreign colleges, from far Russia in the West to Japan and India in the East, I am led to believe that any instruction is useless if it is not kept up to the end of the college course; that whatever the student has studied in one year and then drops, is of little benefit to him. To prove this, last year we gave our electrical engineering students shortly before graduation an examination in mathematics, in those branches which they had concluded in the sophomore year. The results were startling. This year the assistant professor of electrical engineering is giving one hour a week in mathematical subjects, to the junior as well as to the senior classes, with home work in applied mathematics. This has resulted in great improvement in the attitude of the students regarding the value of mathematics to the engineer.

I do not believe in text-books. I agree that a good text-book is better than a poor instructor. To me, a good text-book is merely a way of ameliorating a little the objectionable effect of a poor instructor, but a good instuctor is vastly superior to the best text-book.

It is gratifying to see the almost universal consensus of opinion, that practical familiarity should precede the mathematical theory of engineering, that the instruction should be built up in gradually widening circles through a study of the appearance, the action, the behavior, and the running of apparatus, and then gradually building up to an understanding of its operation, a study of the theory—ultimately culminating the structure with the most general, the mathematical equation and the most specific, the numerical calculation. A further development of this idea, carrying out this principle, is Professor Karapetoff's concentric method. I thoroughly believe in it. But there are difficulties in the way: experience proves that an intelligent and ambitious workman who has become familiar with electrical apparatus by operating it, or working in electrical factories, is anxious to find out the why and wherefore of a machine. Frequently the student is liable to be listless in this respect. When he has gone over the subject in a practical way first, and then goes over the same subject theoretically and more thoroughly, he is liable to neglect it because he thinks he knows enough about it. This means, to introduce better and more modern methods, we must start farther back, with the high school, and beyond the high school. A large part of the defects of the college education are really defects inherited by the college from the high school and the primary school and there is where the lever must be applied to improve conditions. The second serious difficulty is that before we can modernize and improve the education of the college boy we are obliged first to educate the college staff to the realization that conditions are not satisfactory. We are liable there to be met with statements as to what proper pedagogic principles and correct pedagogic methods are, and then we can hardly look for very much co-operation, from men who are satisfied that their way is the only right and proper method.

**A. E. Kennelly** (by letter): The questions under consideration are in one sense of great antiquity, although from another viewpoint they are of very recent origin. They are of great antiquity in the sense that electrical engineering is only a particular kind of engineering, and engineering is coeval with civilization itself. We have only to examine the pyramids of Ghizeh or a Roman aqueduct to realize that engineers existed thousands of years ago, and that such engineers must have received training for their work in some manner. On the other hand, the subject before us is of very modern growth in the sense that *electrical* engineering has made such recent development. Modern methods of instruction in electrical engineering are therefore the latest evolutions of educational training offered to meet the joint demands of the public, the engineering profession, and the engineering student body.

The Educational Committee can, no doubt, render to the Institute valuable service by collecting and collating information concerning the various systems and details of engineering educational methods adopted in different institutions of this country or abroad. It is, however, earnestly to be hoped that the Educational Committee will not seek to standardize engineering education, in the sense of pressing all institutions to follow as nearly as possible one and the same path, term, and system of engineering training. It is perhaps desirable that one and the same college degree in engineering should represent substantially the same amount of training or attainment on the part of the average student, so that it may be proper to attempt standardization in regard to the grading of one and the same degree. It seems undesirable, however, that all colleges or institutions training youths in engineering should grant precisely the same degree, or should offer identically the same training, should receive the same material, or should attempt to turn out the same finished product. It is here contended that what is more desirable is a wholesome diversity of aims, conditions, and training.

We know that in the world of mental activity as well as in the world of physical activity, achievement does not depend wholly upon training; it depends upon inheritance as modified by training. No great athlete, great singer, great engineer, or great worker of any kind was ever produced by training alone. We have the experience of mankind in all historical time to attest this fact. Men are born with an infinite range of capability for achievement in any given division of human affairs; some become eminent without any school or college training; while a great number can never become capable, no matter how much training they receive. All that we know is that training and education will increase each individual's power and capability, whatever that may be. An education is, therefore, an investment on the part of a student in time, money, vitality, and effort, for training to assist his inherited capabilities in his chosen life's work. It seems to be a biological law that the greater the inherent power of an organism, the longer the time and training required to bring this power to its greatest development. The highest types of mankind take the longest training with advantage. It does not pay to train the moderately gifted lengthily and extensively; it does pay to train the highly gifted long and thoroughly. The great bulk of the world's work must be done, and should be done by average men, and where there is room for one leader or colonel of a regiment, there is room and opportunity for creditable work to be performed by hundreds of average men. What is needed, therefore, is not that all institutions should attempt to turn out exactly the same type of graduates in engineering; they cannot, even though they try. Education should be graded to suit the needs of different individuals. We need many more privates and non-commissioned officers in engineering and industrial work than superior officers; and the country can be better served as a whole by offering a greater diversity of periods and types of engineering training. In addition to correspondence schools and evening schools, there is need of the training which can be offered by schools with schedules lasting from three months to six years. Such diverse trainings should be co-operative, in such a manner that a student entering upon a short course and showing ability to receive a longer and more thorough training should be aided in effecting a transfer; and, conversely, a student attempting too long a training should be aided in saving his time and energy by transferring to a shorter course. None of these different schedules would necessarily be superior or more worthy than another; they would all be equally important to the community as a whole.

**H. B. Coho** (by letter): We all know that fully 50 per cent. of the graduates from our technical schools and colleges receive their degree, not by any very brilliant actions or effort on their own part, but by the grace of their alma mater. These degrees are, therefore, heavily discounted, and their value is problematical. The average boy goes to college because it is an eminently respectable thing to do; he acquires a social standing, and an acquaintance, the value of which is well known. He enters the institution often on a diploma from a high school or preparatory school, which certifies that he has had a certain amount of opportunity to study a given quantity of subjects, and ought to know something of them.

To my mind the degree of a technical school ought to mean something absolutely, or else it should not be given; and I am firmly convinced that the degree of electrical engineer should be conferred by the American Institute on such of their members as can pass a given examination, and show at least three years' practical experience in the line of their chosen profession; this degree should be open to the artisan as well as to the college-bred man that can qualify.

My opinion is that the remuneration of college professors has comparatively little to do with the results, as I doubt very much whether our captains of industry would make good teachers, and, *vice versa*, whether our teachers would make satisfactory captains of industry. To make a success of anything, a man must devote his time and thought to the subject in hand, without heeding the money recompense. The mere lust for money is easily satisfied, but the lust for power and achievement cease only at death.

Before a piece of steel can be sharpened it must be tempered; so with the human mind, the mind must be trained before it is ready to receive the finer impressions.

As Dr. Steinmetz has said, then, the improving of the lower grades must be carefully attended to, The boy is the father to the man, and we all know that it is impossible to obliterate entirely impressions received during the first ten years of life, therefore, the importance of giving care and attention to the primary and secondary grades in our public schools is apparent.

To my mind, our school system should be so devised as to give a pupil from the beginning individual attention, treating him as a unit, and not as a class, and keeping a careful record of his work throughout his whole school life, so that when he reaches the age where a selection of occupation is to be made he can be advised and guided. By making his entrance to college or technical school dependent not only upon his ability to answer a certain list of questions, but also on his record, we shall greatly improve upon the material which our teachers will have to deal with; the product of our educational institutions will then be men, capable of taking up life's problems in an intelligent manner.

**A. S. McAllister** (by letter): The fact that a large percentage of the graduates from engineering colleges prove unsuited for engineering work, as stated by a speaker who is exceptionally well qualified to make observations, is one that has as yet not received the proper amount of consideration from those interested in the education of our boys. The present writer believes that the college courses and methods of instruction furnish only a small part of the cause for the result. During my short teaching experience, I became thoroughly convinced that many of the students that came under my observation were much better qualified for some line of study different from engineering rather than for engineering itself. The fact that a student makes indifferent progress in engineering does not prove either that he is lacking in brain matter or that the method of engineering instruction is incorrect; in many cases his parents or the advisers of the student during his high-school days are at fault. It is absolute folly to attempt to make an engineer out of a student who during his high-school days shows not only no taste for physics and mathematics but is innately averse to all studies that appeal to the reason rather than to the memory. There are students who display no marked inclinations along any certain line of study, while there are others who seem to enjoy all lines. The latter, however, are the exception rather than the rule. A fact that should always be kept in mind by those in position to decide whether certain boys shall attempt engineering college work or take up other duties immediately after leaving high school is that a college can develop latent talents but that it cannot put brains into an empty skull; it cannot make an engineer out of a boy whom nature has deprived of well arranged reasoning faculties. It would obviously be very improper for anyone to claim that an engineer, like a poet, is born and not made. However, it can be truly stated that the chances for success are infinitely greater for that boy who selects a career in conformity with his natural talents, than for one who adopts a profession merely because his parents consider it one in which the average compensation is comparatively high. Many of the third-rate lawyers and doctors of the present day could have made excellent engineers; many of the present day inefficient engineers could have become first-class doctors or lawyers. It is an absolute injustice to the student to allow him to undertake one line of work for which he has no talents, and thereby permit his natural talents which lie along other lines to remain dormant. The entrance requirements should be arranged in such a way as to determine for what line of work a boy is best suited, in order that he may secure the maximum good from the time spent in college, and the instructors may obtain the best results from their labors.

**W. S. Franklin** (by letter): My hobby is mental arithmetic. The ability of a student to follow a simple physical argument depends vitally upon his power to hold numerical relations in mind, and the greatest difficulty that I encounter in my work of teaching elementary physics arises from lack of this kind of arithmetical sense on the part of the student. For many years I have tested my junior students with the question: "When does a growing thing reach its greatest size?" I have found but one student in all my experience who was ready with the simple arithmetical answer: "When it stops growing". And yet nearly every man in every class could have filled a blackboard with algebraic formulas in response to a formal question concerning the maxima and minima of an algebraic function.

In discussing the ballistic galvanometer, one arrives at the proposition that the rate at which the suspended needle gains angular velocity is proportional to the rate at which charge flows through the coils, from which one argues that the total angular velocity gained is proportional to the total discharge. I always illustrate this point by asking the class to consider one man who saves money ten times as fast as another, whence it may be argued that the one man must always have ten times as much money as the other, if they get an even start, and then I ask the class what this argument is called, but never yet have I found a single student who had a sufficiently simple idea of calculus to know that this arithmetical argument is called integration.

I have always had a desire to use the algebraic forms of calculus in my teaching of elementary physics, but the weakness of most students in the simpler branches of mathematics and the almost universal lack of arithmetical sense (the holding of numerical relations in mind) has forced me to the conclusion that it is ridiculous at the present time for any teacher to attempt to use calculus in the handling of any subject in the class-room. I think it is no exaggeration to say that ninety-nine per cent. of the technical graduates with whom I have conversed have admitted their total lack of understanding of the subject of calculus when they took it in the technical school. If most of us did not stand in awe of mathematics, such a state of affairs would lead us instantly to the conclusion that something was radically wrong, but it seems that most men are still imbued with the idea expressed many years ago by the great English mathematician, Sylvester. Sylvester showed an unusual aptitude for mathematics while still an undergraduate, and he said that he was pointed out by his mates as a man who, like Dante, had seen Hell, the idea being that mathematics was not supposed to be understood by the great mass of students who were required to study it. Now I contend that calculus must be understood by the great majority of men who study it, or it must cease to be taught; and I believe that the reduction of calculus teaching to the plane of old-fashioned mental arithmetic would go a great way towards meeting this situation.

**O. J. Ferguson** (by letter): A man goes to college to save time by concentration. All that he acquires there can be obtained elsewhere and by other methods, but the operation of these other methods is subject to so many interruptions and diversions that the efficiency rate at which the work is done is low.

No college training of a few years can fit a man to occupy positions of great engineering responsibilities. It must be augmented by experience. During college life he is considering the available results of experience of others, but man is so constituted that he must learn ultimately by his own personal contact with facts.

Of these two components of his training we are discussing the one which comes under the direction of instructors. The most important things to be considered therewith are, in the broadest sense:

1. Methods of thought.
2. Fundamental truths.
3. Allied subjects.
4. Average data.
5. Experience—enough to serve as illustrations and as "labels" for theory.

No engineer who comes into contact with men recently graduated from colleges can fail to note the general inability of their minds to grasp important details, sift, summarize, reason logically, and analyze keenly. All minds are not equally endowed in these respects, but training should bring out whatever exists of these all-important requisites to the engineer.

Mathematics is the purest of logical and analytical reasoning, and, considered even wholly aside from its utility, should be placed in the first years of college work and never wholly omitted later in the course. Its value lies in the fact that it permits clear, concise, definite statements, and demands proof of every step from its "Given" to its "Q. E. D." It should progress from the pure to the applied, and to broad engineering practice which is richer in problems than is the mind of any author of mathematical text-books.

Facts are of several kinds: Truths, facts of to-day, facts of yesterday, and things that never were so. Fundamental truths should be distinguished from current practice. Keep up with the times but do not lead students to accept offhand the things of to-day as the standards of to-morrow. One can devote too much time to practice to obtain breadth of view.

Allied subjects should be taught, not from the electrical engineer's view, but broadly and carefully though not in detail from the point of view of the specialist. For, no matter what we are using or are not using now, the future will demand more from us.

Average data of existing normal practice should be analyzed for fundamentals. Machine shop and laboratory work are beneficial so far as they serve to clarify ideas of machinery, circuits, and power development, transformation and measurement, and to illustrate methods of reasoning in the study of problems. As before indicated, they are the pictured labels attached to carefully stored bits of information and are to be used as identification marks in selecting such data for comparison with subsequent experience. A great deal of the time spent in manual training, etc., is of little value compared with what might be accomplished by a better use of the same time. Personal experience should not be allowed to intrude itself into any curriculum at the expense of concentration upon the main line of thought.

As for the order in which certain studies are met, I believe it is better to prepare the broad foundation first with its tendencies toward habits of scientific reasoning and research—painstaking and deliberate. Theory can at first be stripped of its "negligible quantities" and is still intricate enough for the beginner. Practice can never eliminate these minor influences which serve to hide to a greater or lesser degree the principles sought, although they may not seriously influence the problem at hand.

**C. O. Mailloux** (by letter): The lecture system is objectionable, in my opinion, so far as, and to the extent that, it robs a student of the time and the energy requisite to study his notes properly, because too much time and energy have to be consumed in taking the notes and, especially, in correcting, rearranging, completing or rewriting them; in a word, in making them "fit" to study. A certain amount of "going over" the notes, on the part of the student, is, in my opinion, desirable; but much of its beneficial effect is lost when the notes are incomplete and incorrect because the student was not able to follow the lecturer. Unfortunately, this occurs much more often than ought to be the case. It is for this reason that the syllabus and book of reference becomes valuable, if not indispensable, as a means for filling the gaps and voids, and of mending lame notes containing incomplete or incorrect diagrams, formulas, etc. It does seem as if much of the student's time and energy, that now has to be devoted to correcting and amplifying his notes, might be devoted to studying them. After observing and studying carefully the methods of some forty or more lecturers on technical subjects, from the dual standpoint of student and teacher, I am of the opinion that the shortcomings of the lecture-system of instruction are more often due to the lecturer than to the lecture-system; and that it would be only necessary, in many cases, to improve the method of the lecturer, in order to improve the results of the system. The ideal system, in my opinion, is a lecture-system, in which the lecturer, either by dictation or by writing out in sufficient detail on the blackboard, or by means of a good syllabus, simplifies the student's task of getting accurate notes, and, at the same time, allows him time to follow the reasoning, demonstrations, and discussions presented. It is too often the case that the student is so busy with the mechanical work of taking down notes, that he is totally unable to follow, much less to absorb and digest, the subject-matter presented. In such cases, it is obvious that the method of teaching by lectures is much inferior to that of teaching by the text-book system. As already stated, however, the fault lies more with the particular method of the lecturer than with the lecture-system.

**H. W. Blake** (by letter): On one point all engineers are agreed, namely, that it is impossible to crowd into a four-years' course all of the instruction which the young electrical engineer will find useful after graduation. If this is true at the present time, it is evident that as the art advances year by year it will be necessary still further to circumscribe the number of subjects included in the required courses. This will involve yearly additional sacrifice of instruction in those branches, which are classed by one speaker as " cultural and scientific " rather than purely technical.

The engineering schools are now attracting many men whose fields of activity after graduation are almost as varied as those of the graduates in the academic or arts department. These men would formerly have matriculated in the older college course, but the inclusion into so many lines of industry now of engineering principles makes an engineering education a desideratum. At the same time, a knowledge of the purely technical branches of the subject is not so important for many of these students as a good acquaintance with such topics as business-law, rhetoric, and modern languages, and the ability to meet the political and economic questions which are apt to arise in the administration of engineering undertakings.

The technical educator is, then, face to face with a serious dilemma. Should he confine his curriculum to the purely technical studies which experience has shown require the entire time of the undergraduate to master, or should he subordinate some of them to those cultural and scientific branches desired by a large number of men entering the technical schools yearly? The answer to this question is really dependent upon a decision whether it is possible to introduce electives in an engineering school to the same or nearly the same extent as in the arts course. One reason advanced for not following this plan is the expense of supplying the varied instruction, but this hardly applies in universities, where these outside courses are taught in other departments. Another objection has been the question of degree, because the title of engineer, civil, mechanical, or electrical, awarded at the end of the course, is generally considered to imply familiarity with certain prescribed studies. This objection may be valid and may not. Certainly, however, the tradition is not as venerable as that which limited the degree of B.A. to a college course which should include at least two years of study in Latin and Greek. This requirement is no longer in force in many leading universities. If necessary, the engineer's degree could be reserved for a post-graduate course along certain well-defined lines. The chief point is that the electrical engineering industry is now calling for many men whose training should primarily be along engineering lines, but who also require certain instruction which the technical schools cannot give unless they incorporate into their curricula a liberal system of electives.

**Dugald C. Jackson** (by letter): Many excellent words are said in the two brief papers which have been presented by Mr. Scott and Dr. Steinmetz, but I am compelled to take the view that neither of the papers makes any constructive suggestions which may lead to an advance in engineering education. Perhaps the nearest suggestion that comes to that point is to be found on the first page of Dr. Steinmetz's paper, where he refers to the importance of close coöperation between the electrical industries and the engineering colleges. That coöperation is growing up rapidly as a matter of necessity, but it has heretofore been more or less undirected, and I had hoped that the papers of this evening would give us some suggestions for making more out of that effort. This is surely an important question for the Educational Committee carefully to consider and digest with a view of bringing up concrete and constructive proposals. Dr. Steinmetz makes the interesting statement that the existing coöperation probably constitutes the strongest feature of American engineering education. I am in partial agreement with him, but I am by no means in agreement with what I understand to be his implication that the present coöperation is as effective or intimate as it should be. I will not here undertake to enter into the enumeration of the reasons for my views, but will perhaps undertake to do so at some later date.

In this connection I wish to call attention to Mr. Scott's statement that a fairly intimate intermingling of college work with practical work will be found to conduce to the efficiency of each, and I wish to express my hearty sympathy with that statement. I believe that much can be done in the way of improving our present electrical engineering education by increasing and strengthening the kind of coöperation which is suggested in this sentence of Mr. Scott's.

Mr. Scott's paper seems to indicate that he stands for Professor Karapetoff's plan, which has been dubbed the "concentric method", but I am sure that Mr. Scott could not be the unqualified supporter of that plan had he submitted Professor Karapetoff's proposals to a detailed analysis. The plan which has been presented under the name of the "concentric method" is one which naturally catches the attention of a busy industrialist, and it may hold his attention until the conditions of his industrial work will give him leisure to analyze carefully the processes described. Then he will find that the details proposed by Professor Karapatoff are subject to serious criticism as being in opposition to the basal tenets of pedagogy; though the general plan does not differ very much from the plan which is in operation, with marked success, in several of the best engineering schools. Given time on my part and leisure on the part of Mr. Scott, I will undertake to convert him to my view on this matter, with the understanding that that conversion will be permanent because it will be based upon sound reasoning.

The defects which Dr. Steinmetz points out in the second page of his paper will be admitted by thoughtful and experienced teachers of engineering, but it is happily a fact that these defects are being slowly cleared away. The rate of improvement is so slow as to be exceedingly discouraging when considered year by year, but the aggregate improvement which has been made in the past decade is so marked as to give good ground for optimism in respect to this part of engineering education.

In this connection I wish to point out that Dr. Steinmetz seems to possess a misapprehension in respect to the ideals of some of the better engineering schools. It cannot be properly said that the students in all of the engineering schools are allowed the opportunity to take up the important basal subjects and are then intentionally allowed to drop them without succeeding drill in their applications. The fact is that the mathematics, the chemistry, the physics, the applied mechanics, and the more distinctly professional studies following thereafter should be closely correlated and dovetailed into each other, the order of the work being planned with due consideration of the coördination of the subjects; and care is taken to effect this coördination in certain of the engineering schools. Dr. Steinmetz is probably right in criticizing the arrangement of most electrical engineering courses from this point of view; but, unquestionably, the ideals lying behind the teaching in several of the electrical engineering courses give due and full consideration to these factors; and, indeed, no course can be carried on with fair consideration of the best known principles of pedagogy without including provisions for these factors. The worst features of many of our engineering courses have arisen from the fact that so much of their work has been introduced without consideration of the pedagogical sequence of the parts or the relation of each part to the whole.

Mr. Scott ventures the prediction that the solution (which will find the most general acceptance) of the problem of what is the best engineering education, will be that which gives to each student the training that fits him for his best individual development. In these words Mr. Scott has stated an important principle in education, and he is to be heartily thanked for putting the matter so plainly. To get a fundamental principle clearly in mind is often half the battle. But Mr. Scott leaves us still groping, because he gives no adequate indication of the direction in which engineering courses may be improved for the purpose of gaining the goal which the principle lays down. The same may be substantially said of Dr. Steinmetz's paper. Dr. Steinmetz remarks that the present condition in the industries, wherein men who have never had a college education may rise ahead of college graduates, would be impossible if our engineering courses gave what they should, namely, an intelligent understanding of electrical engineering subjects. But the difficulty under which we now labor is to lay our finger on the specific improvements which can be and should be effected for the purpose of affording this intelligent understanding of electrical engineering subjects that Dr. Steinmetz asks for. What the engineering schools need now is careful analytical scrutiny of their processes of work, and constructive suggestions for changes which will bring about improved results.

I believe that the better engineering schools have a lively understanding of their defects, and a well-developed desire to overcome them, but a difficulty resides in determining what improvements will bring the wished for results. Experiments in education generally require years of trial before their effects can be clearly discerned, and experiments must therefore be made with caution to prevent taking any backward step.

I wish to say a word in regard to the remarks of two or three other members who entered into this discussion. In respect to Mr. Ferguson's remarks, I believe that I can say that I heartily agree with the whole of his presentation; and I also want to express my appreciation of Professor Clifford's admirable presentation of the requirements in engineering education. I would like to emphasize, more than Professor Clifford's remarks emphasized, the necessity of adding those things which lead to the education of judgment; and my acquaintance with Professor Clifford assures me that he probably agrees with me on this point.

Mr. Stillwell directs attention to the proposal that the ideal education for engineers is going to be brought about by the plan which is now being shouted as a shibboleth from the housetops—an arts course first and an engineering course afterward. I do not believe that this is a solution of the difficulties which are outlined in the papers of the evening, and I believe the plan was originally conceived by men who are unacquainted with the necessities of engineering education. These men may have a profound knowledge of the great results that come from a proper pursuance of the old-time arts course, but this does not give them the experience or the power which makes them sound leaders in the problem of engineering education. I believe it is a misfortune that such admirable engineers as Mr. Stillwell are willing to lend themselves to the promulgation of this plan without a full and complete analysis of its results. I heartily agree that an engineer needs to be a broadly and completely educated man; but where two horses are to be driven it is better to drive them side by side (in parallel) rather than in tandem, if one aims at effective power and not merely at showy results. It seems to me that the engineering course, to be fully effective, should include the physics and the chemistry and the mathematics and much of the general studies in the engineering school, and subjects such as political economy, history, and the languages may be appropriately carried out to the end of the course. This, indeed, is a factor which I understand Dr. Steinmetz approves, and it is this suggestion contained within the so-called "concentric method" which I presume attracts Mr. Scott's friendly attention. The failure of the concentric method lies distinctly in the repetitions of work which it recommends. There may be a real utility in the modified proposition which is now beginning to gain vogue amongst the best thinking men of the engineering schools, and also of the literary and classical colleges, which proposes that students shall spend perhaps two years under the influences of the arts course and shall then spend four years under the conditions of the engineering school. This would make the engineering school base its entrance requirements upon attainments gained by the students from two years of the arts course in college or university, and the plan comprises many factors which indicate its utility as an educational plan. The plan urged by Mr. Stillwell calls for three or four years in the arts course and then for two or three years in the engineering school; but this abbreviates the engineering course to a degree which makes the joint work relatively ineffective, besides giving the students a misapprehension of the relative importance of their historical and literary studies compared with their technical studies (by substantially dismissing the former from their attention for several years while the technical studies are being pursued) and leading them to the erroneous belief that the humanistic studies do not belong to their lives as engineers.

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# THE SINGLE-PHASE COMMUTATOR-TYPE MOTOR

BY B. G. LAMME

The broad statement may be made that it is no more difficult to commutate an alternating current than an equal direct current. Such a statement would appear to be entirely contrary to the usual experience, but a little study of the matter will show where the apparent discrepancy lies. In commutator type alternating-current motors, as usually built, a relatively large number of commutator bars pass off under the brush during one alternation of the supply current. While the current supplied is varying from zero to maximum value and back to zero, possibly 50 bars have been passed under the brush, and therefore 50 coils in the armature have been reversed or commutated. Some of these reversals occur at the top of the current wave which has a value of about 40% higher than the mean or effective value which is read by the ammeter. The motor is therefore at times commutating 40% higher current than that indicated by the instruments. It is thus evident that in comparing the commutation of 100 amperes direct-current with 100 amperes alternating-current we should actually compare the direct-current with 141 amperes alternating. In other words, for commutating equal currents alternating-current or direct-current, the alternating-current ammeter should register only 71% as much current as the direct-current. Another way of expressing it is that we have to commutate the top or maximum of the alternating-current wave, while our instruments only record the mean value.

If the above represented the only difference between the alternating current and direct current the problem to be solved in commutation of alternating current would not be serious.

However, the current to be commutated by an alternating-current motor is not merely the working current supplied to the motor and measured by the ammeter, but there is, in addition, a current which is generated in the motor itself, both at standstill and during rotation, which has to be reversed or commutated along with the working current. It is this latter current, usually called the local or short-circuit current, which has been the source of greatest trouble in commutating alternating current; for this short-circuit current may have a value anywhere from three to ten times the working current, depending on the design of the machine. Therefore in comparing the commutation of an alternating current, as indicated by an ammeter, with an equal direct current, we should, in reality, consider that the alternating-current motor is commutating a maximum current from five to ten times the value of the indicated current. Furthermore, it would not do to reduce the ammeter current to one-fifth or one-tenth value in order to compare commutation with direct current, because by so doing we would simply be reducing the small applied component of the total current commutated by the brushes, the local or short-circuit current still retaining a rather high value. In order to compare with direct-current commutation, it would be necessary for the total maximum of the combined supply and the short-circuit current to be reduced to the same value as direct current.

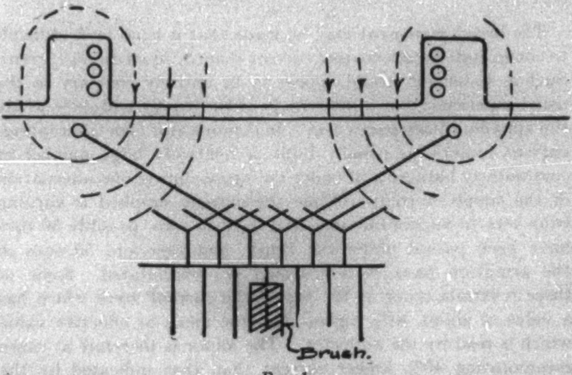

FIG. 1

It is the local current in the armature turn short-circuited by the brush which is the source of practically all the trouble in commutating alternating currents. Fig. 1 illustrates a portion of the field and armature structure of a commutator type alternating-current motor. It will be noted that the armature conductor, which is in the neutral position between poles, surrounds the magnetic flux from the field pole, just as the field turns themselves surround it. The field flux being alternating, this armature turn will have set up in it an electromotive force of the same value as one of the field turns. Short-circuiting the two ends of this armature turn should have the same effect as short-circuiting one of the field turns, which is the same thing as short-circuiting a turn on a transformer. Such a short-circuited turn, if of sufficiently low resistance, should have as many ampere-turns set up in it as there are field ampere-turns. In single-phase motors of good design the field ampere-turns per pole are about twelve to fifteen times the normal ampere-turns in any one armature coil. Therefore, if the armature coil in the position shown in this Fig. 1 should have its ends closed on themselves the current in this coil would rise to a value of twelve to fifteen times normal. In reality, it would not rise quite this much, because this armature turn is placed on a separate core from the field or magnetizing turns with an air-gap between, so that the magnetic leakage between the primary (or field winding) and this armature (or secondary winding) would tend to protect this coil somewhat, just as leakage between the primary and secondary windings of a transformer tends to reduce the secondary electromotive force and current. Also, this armature coil is embedded in slots, thus adding somewhat to its self-induction, and tending further to reduce the short-circuit current. In consequence, with its ends closed together the current in this armature coil would probably not rise more than ten to twelve times above normal value under any condition. It is evident, therefore, that if the brush shown in Fig. 1 as bridging across two commutator bars to which the ends of this coil are connected is of copper or other low-resistance material, then there could be an enormous local current set up in the coil when thus short-circuited by the brush. This local current of about ten times the normal working current would have to be commutated as the brush moves from bar to bar, and therefore the operation of the machine would be similar to that of a direct-current motor if overloaded about ten times in current. In other words, there would be vicious sparking.

Even if the low-resistance brush were replaced by one of ordinary carbon, the short-circuiting current would still be relatively high, due to the fact that it is not possible to make the brush contact of very high resistance by reducing the size or number of the brushes, because these same brushes must carry the working current supplied to the motor, and there must be brush capacity sufficient to handle this current. This brush capacity will, in practice, be of such amount that the resistance in bridging from one bar to the next is still rather low, although much higher than if a copper brush were used. Experience shows that with not more than four or five volts generated in this short-circuited coil by the field flux, the resistance of the carbons at the contact with the commutator would be such that a short-circuit current of three to four times the normal working current in the coil can still flow. Therefore, if the motor were equipped with carbon brushes and had but four or five volts generated in the short-circuit coil, the motor would have to commutate the main or working current and also a short-circuit current of possibly three times the amount. This short-circuit current would also have a maximum or top of its current wave. Assuming 100 amperes as the current supplied to the motor, the machine therefore actually commutates a supply current of 141 amperes and an additional short-circuit current of possibly three times this value, or from 400 to 500 amperes, therefore, the motor actually commutates the equivalent of about 600 amperes direct current when the alternating-current ammeter is reading 100. It is evident from this that any one who tries to commutate alternating current with an ordinary type of commutating machine would at once draw the conclusion that alternating current in itself is very difficult to commutate, naturally overlooking the fact that it is the excessive current handled by the brush that is back of the trouble, and not the current indicated by the ammeter.

From what has been stated, it is evident that the excessive local current is back of the difficulty in commutating alternating current. All efforts of designers of alternating-current commutator motors have been in the direction of reducing or eliminating this local current. The present success of the motor, in the various forms brought out, is largely due to the fact that this current has been successfully reduced to so low a value that it does not materially add to the difficulties of commutating the main current. No successful method has yet been practically developed for entirely overcoming the effects of this short-circuit current under all conditions from standstill to highest speed. Some of the corrective methods developed almost eliminate this current at a certain speed or speeds, but have little or no corrective effect under other conditions; other methods do not effect a complete correction at any speed, but have a relatively good effect at all speeds and under all conditions. The former methods would appear to be applicable to motors which run at, or near, a certain speed for a large part of the time; the latter method would be more applicable to those cases where the motor is liable to be operated for considerable periods with practically any speed from standstill to the highest. While several methods have been brought forward for correcting local current when the motor has obtained speed, yet up to the present time but one successful method has been developed for materially reducing this current at standstill or very low speeds. It may be suggested that the short-circuit voltage per coil be reduced to so low a value, say four or five volts, that the local current is not excessive and does not produce undue sparking. This would certainly reduce the sparking difficulty, but is open to the very great objection that the capacity of the motor is directly affected by a reduction in the short-circuit voltage. This voltage per turn in the armature coil is a direct function of the value of the alternating field-flux and its frequency. Assuming a given frequency, then the short-circuit voltage is a direct function of the induction per field pole, and the lower the short-circuit voltage the lower must be the field flux. But the output of the machine, or the torque with a given speed, is proportional to the product of the field flux per pole by the armature ampere-turns. In a given size of armature the maximum permissible number of ampere-turns is pretty well fixed by mechanical and heating considerations, and therefore with a given armature the torque of the motor is a direct function of the field flux. Using the maximum permissible armature ampere-turns, the output of a given motor would be very low if the field flux were so low that the short-circuit voltage would not be more than three or four volts. Increasing the field induction, and therefore increasing the short-circuit voltage, increases the output.

Experience shows that on large motors, such as required for railway work, the induction per pole must necessarily be so high that the electromotive force in the short-circuit coil must be about double the figure just given; therefore, with such heavy flux the short-circuited current will necessarily be excessive unless some corrective means is used for reducing it.

I will consider the standstill or low-speed conditions first. For this condition only one practical arrangement has so far been suggested for reducing the local current to a reasonably low value compared with the working current. This method involves the use of preventive leads, or, as they are sometimes called, resistance leads. These consist of resistances connected between the commutator bars and the armature conductors. Fig. 2 illustrates the arrangement. The armature is wound like a direct-current machine, except that the end of one armature coil is connected directly to the beginning of the next

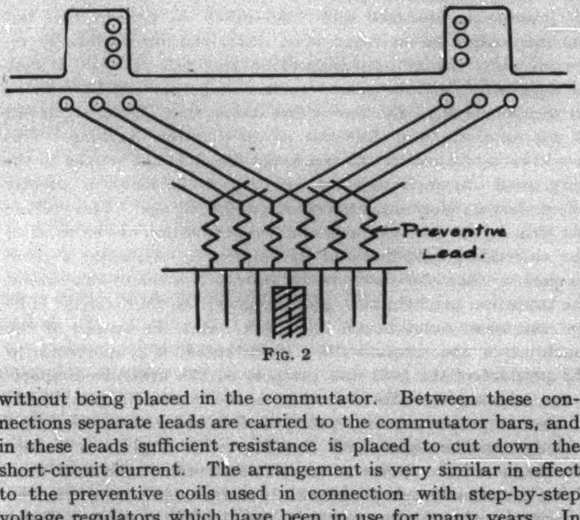

FIG. 2

without being placed in the commutator. Between these connections separate leads are carried to the commutator bars, and in these leads sufficient resistance is placed to cut down the short-circuit current. The arrangement is very similar in effect to the preventive coils used in connection with step-by-step voltage regulators which have been in use for many years. In passing from one step to the next on such regulators, it is common practice to introduce a preventive coil or resistance in such a way that the two contact bars are bridged only through this preventive device.

In an armature winding arranged in this way, the working current is introduced through the brushes and the leads to the armature winding proper. After entering the winding, the current does not pass through the resistance leads because the connections between coils are made beyond these leads. In consequence, only a very small number of these leads are in circuit at any one time; when the armature is in motion all the leads carry current in turn so that the average loss in any one lead is very small. As the brush generally bridges across two or more commutator bars, there is usually more than one lead in circuit, but generally not more than three. When the brush is bridging across two bars, there is not only the working current passing into the two leads connected to these two bars, but there is the local current, before described, which passes in through one lead, through an armature turn, then back through the next lead to the brush. There are losses in these two leads due to these two currents. By increasing the resistance, the loss due to the working current is increased, but at the same time the short-circuit current is decreased. As the loss due to this latter is equal to the square of the current multiplied by the resistance, it is evident that increasing this resistance will cut down the loss due to the local current in direct proportion as the resistance is increased. When the working current is much smaller in value than the short-circuit current, an increase in the resistance of the leads does not increase the loss due to the working current as much as it decreases the loss due to the short-circuit current. Both theory and practice show that when the resistance in the leads is so proportioned that the short-circuit current in the coil is equal to the normal working current, the total losses are a minimum. Calculation, as well as experience, indicates that a variation of 20% to 30% at either side of this theoretically best resistance gives but a very slight increase in loss, so there is considerable flexibility in the adjustment of this resistance. The resistance of the brush contacts and of the coil itself must be included with the resistance of the leads in determining the best value. In practice it is found that with ordinary medium-resistance brushes, the resistance in the leads themselves should be about four or five times as great as the resistance in the brush contact and the coil; that is, we usually calculate the total necessary resistance required and then place about 70% or 80% of it in the leads themselves. When leads of the proper proportion are added to the motor, it is found that practically twice as high field flux can be used as before with the same sparking and burning tendency as when the lower flux is used without such leads. But even with six to eight volts per commutator bar as a limit, we are greatly handicapped in the design of the motors, especially when the frequency is taken into account. This limited voltage between bars also indicates at once why single-phase railway motors are wound for such relatively low armature voltages. Direct-current railway motors commonly use from 12 to 20 volts per commutator bar, or from 2 to 2.5 times the usual practice on alternating-current motors. With this low voltage between bars in alternating-current machines, with the largest practicable number of bars, the armature voltages become 200 to 250, or about 40% of the usual direct voltages. The choice of low voltage should, therefore, not be considered as simply a whim of the designers; it is a necessity which they would gladly avoid if possible.

Assuming preventive leads of the best proportions, let us again compare the current to be commutated in an alternating-current motor with that of the direct-current. Considering the ammeter reading as 100, the working alternating current has a maximum value of 140 and in addition there is a short-circuit current of same value. Even under this best condition, the alternating-current motor must commutate a current several times as large as in the corresponding direct-current motor. The design of such a motor, therefore, is a rather difficult problem, even under the best conditions.

While resistance leads theoretically appear to give the most satisfactory method for obtaining good starting and slow-speed running conditions, yet other methods have been proposed. The only one of any practical importance is that in which the short-circuit voltage is reduced at start and at slow speed by sufficiently reducing the field induction. As this reduced field induction would give a proportionately reduced torque, it is necessary at the same time to increase the armature ampere-turns a corresponding amount above normal. This is only a part solution of the problem, however, for the decrease in short-circuit current by this means is partly offset by the increase in the working current, so that the total current to be commutated is not reduced in proportion to the field flux. Where the period of starting and slow running is very short, this method is fairly successful in practice. However, with this arrangement it is rather dangerous to hold the motor at standstill for any appreciable length of time, for in such a case the large short-circuit current is confined to a single coil and the effect is liable to be disastrous if continued for more than a very short period. With this method of starting, the total current handled by the brushes will usually be at least two to three times as great as when preventive leads are used.

The preceding statements refer mainly to starting or slow-speed conditions. When it comes to full-speed conditions, however, there are various ways of taking care of the commutation. One of these methods is based on the use of preventive leads, as described; the other methods depend upon the use of commutating poles or commutating fields in one form or another.

It is evident, from what has been said, that at start the preventive leads which reduce the short-circuit current to low values will also be effective in a similar manner when running at normal speed. Such a motor with proper proportion of leads will, in general, commutate very well at full speed when the starting conditions have been suitably taken care of. Nothing further need be said of this method except that the tests show that the short-circuit current has considerably less value at high speed than at start.

The other methods of commutation at speed, involving commutating poles and commutating fields, necessarily depend upon the armature rotation for setting up a suitable electromotive force in the short-circuit coil to oppose the flow of the short-circuit current. As the electromotive force in the short-circuited coil is a direct function of the field flux, and is independent of speed, while the correcting electromotive force is a function of the armature speed, it is evident that either the commutating pole can produce the proper correction only at one particular speed, or the strength of this commutating pole must be varied as some function of the speed. Usually the strength of these poles is made adjustable with a limited number of adjustments and approximate compensation only is obtained on the average. In the Siemens-Schuckert motor the commutating poles are of small size and placed between the main poles. These are for the purpose of obtaining commutation when running. In addition the armature is provided with preventive leads for improving the operation at start and at slow speed. In the Alexanderson motor, according to published description, no separate commutating poles are provided, but the edges of the main poles are used as commutating poles, the armature coil having its throw shortened until its two sides come under the edges of the main poles. In this motor the field is weakened and the armature ampere-turns are increased while starting. The commutating-pole scheme in this motor is, in some ways, not as economical as in the Siemens-Schuckert arrangement, as the motor requires a somewhat higher magnetization with a consequent reduction in power-factor. The Winter-Eichberg motor is quite different in arrangement from any of those which I have mentioned. I will not attempt to describe this motor in full, but will say that it has two sets of brushes in the armature, one of which is short-circuited on itself, and carries the equivalent of the working current in the types I have described, while the other carries the magnetizing or exciting current which is supplied to the armature winding instead of the field. The arrangement is such as to give practically the same effect as a commutating pole or commutating field. When starting, the field flux is decreased and the armature ampere-turns increased.

All of the above motors are nominally of low armature voltage and all of them appear to commutate reasonably well at speed. Two of them use the full-speed induction at start, while the other two use reduced induction and increased armature ampere-turns at start.

There has been considerable discussion during the last year or two regarding the most suitable frequency for single-phase commutator type motors. It may therefore be of interest to consider what effect reduction in frequency would have on the commutation, output, and other characteristics of the motor.

The short-circuit voltage, as I have stated before, is a function of the amount of field flux and of the frequency. For a given short-circuit voltage the induction per pole can be increased directly as the frequency is decreased. If a certain maximum induction per pole is permissible at 25 cycles, then with 12.5 cycles, for example, the induction per pole may be double, with the same short-circuit voltage. This would at once permit double output if the saturation of the magnetic circuit would permit the doubling of the induction. But on 25-cycle motors, as usually built, we work the magnetic flux up to a point just on the verge of saturation, so to speak, as indicated in Fig. 3. It is evident that double induction, under such conditions, would not be practicable unless the 25-cycle motor had been worked at an uneconomically low point. However, an increase of 30% to 40% in the induction would appear to be obtainable, but a large increase in excitation is required. With but 30%

to 40% higher induction, and with the frequency halved, the short-circuit voltage would be but 65% to 70% of that with 25 cycles or, in other words, the voltage per turn in the field coil is but 65% to 70%. As the higher induction raises the armature counter electromotive force the field electromotive force can be increased in proportion for the same power-factor, or can be 30% to 40% higher than with 25 cycles. As the total field voltage, therefore, can be 30% to 40% higher, and the voltage per field turn is but 65% to 70%, it is evident that the number of field turns can be doubled without changing the ratio of the field inductive volts to the armature electromotive force. In other words, the field turns can be doubled if the frequency is halved. With the double field turns the field excitation can therefore be doubled, which is the requirement for the increased induction shown in Fig. 3. It is thus evident that halving the frequency will permit higher pole inductions, and therefore higher torque and output, with lower short-circuit voltage and better commutating conditions throughout. Also, this higher field induction is not necessarily accompanied by an increased iron loss, for the lower frequency of the alternating

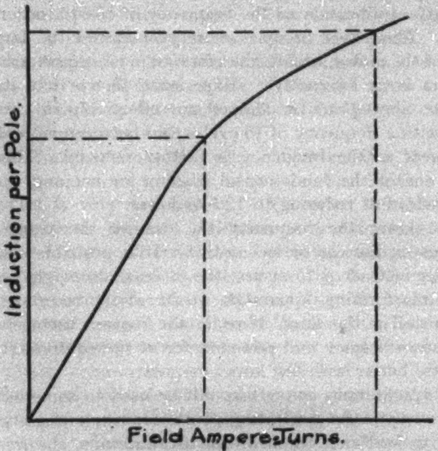

FIG. 3

flux compensates for this. On the above basis it may be asked why a reduction to 15 cycles is proposed instead of to 12.5, or even to 10 cycles. There are several reasons for the choice of 15 cycles.

1. The motor can be worked up to so high a saturation at 15 cycles that there is relatively small gain with a reduction to 12.5 cycles, which would be about the lowest frequency to consider when the transformers and other apparatus is taken into account.

2. As the torque of the single-phase motor is pulsating instead of being constant, as in a direct-current machine, there is liability of vibration as the frequency of the pulsation is decreased. This effect becomes more pronounced the larger the torque of the motor, and is, therefore, of most importance in the case of a large locomotive. Experience shows that this tendency to vibrate can be damped out effectively in very large motors with a frequency of 15 cycles, but becomes more difficult to suppress as the frequency is further reduced. This is, in reality, one of the fundamental reasons for keeping up to 15 cycles instead of reducing to 12.5 or lower.

3. The lower the frequency the heavier the transforming apparatus on the car or locomotive. It is probable that with 12½ cycles instead of 15 cycles, the increase in weight and cost of the transforming apparatus would about counter-balance the decrease in the same items in the motors themselves, although the efficiency and power factor of the equipment would be slightly better with the lower frequency.

4. As synchronous converters will be used to some extent in connection with the generating plants for single-phase systems in order to feed existing direct current railways, the frequency of 15 cycles will be slightly more favorable than 12.5 as regards cost of the converters and the step-down transformers. The same will be true if motor-generators are used for transforming to direct current, also for induction motors.

Against the choice of 15 cycles may be cited the fact that there are other frequencies which represent a better ratio to 25 cycles when frequency-changers are to be taken into account. A low-frequency railway generating plant may require to tie up with some existing 25-cycle or 60-cycle plant; this can be done by interposing frequency-changers. Or it may be desired to obtain a lower frequency with a single-phase current from some existing higher frequency polyphase plant. By interposing the frequency-changer the single-phase railway load will not exert any unbalancing effect on the polyphase supply circuit, and at the same time the railway circuit can be regulated up or down independently of the three-phase generator circuit. In case the three-phase plant is operated at 25 cycles, then a two-to-one ratio of frequencies; that is, 12.5 cycles on the railway circuit, would give the best conditions as regards choice of poles and speeds in the frequency-changer sets. A five-to-three relation is given by 15 cycles, which is not nearly as good as the two-to-one ratio. A frequency of 16⅔ cycles would give a three-to-two ratio, which represents considerable improvement over the five-to-three ratio. Therefore, this slightly higher frequency may prove of advantage in some cases. The choice of this frequency, however, does not mean a new line of apparatus; for a well designed line of 15-cycle motor transformers, etc., should operate very well on a 16⅔-cycle circuit without any change whatever.

When transforming from 60 cycles, however, the 15 cycle gives a four-to-one ratio which is very good, and neither 12.5 nor 16⅔ cycles is very satisfactory. Therefore this 15-cycle frequency represents the best condition in transforming from 60 cycles, and fairly good conditions for transforming from 25 cycles; and by operation of 15-cycle apparatus at 16⅔ cycles a very good transformation ratio is obtained from 25 cycles. It may be of interest to recall that the old Washington, Baltimore and Annapolis Railway, which was the first road contracting for single-phase commutator motors, was laid out for 16⅔ cycles. There was considerable criticism at that time of the use of this frequency, but the statement which I have just made shows one very good reason for this frequency. A second reason is that 16⅔ cycles per second is 2000 alternations per minute, which permits a steam turbine driving a two-pole generator to use a speed of 1000 rev. per min., which is a very good one for large-turbo generators.

I have gone into the question of induction and frequency as affecting the commutation and torque. I will now take up the question of power-factor in the single-phase commutator motor. In a direct-current motor we have two electromotive forces which add up equal to the applied electromotive force; namely, the counter electromotive force due to rotation of the armature winding in the magnetic field, and the electromotive force absorbed in the resistance of the windings and rheostat

In the alternating-current motor there are these two electromotive forces, and there is also another one not found in the direct-current machine; namely, the electromotive force of self-induction of the armature and field windings due to the alternating magnetic flux in the motor. This inductive electromotive force exerts a far greater influence than the ohmic electromotive force for it has much higher values.

The inductive electromotive force lies principally in the main field or exciting winding of the alternating-current motor. There is a certain voltage per turn generated in the field coils, depending upon the amount of the field flux and its frequency, as stated before. This electromotive force per field turn is practically of the same value as the short-circuit electromotive force generated in the armature coil, as already referred to. I have stated that a short-circuit voltage of three or four volts per armature turn gave prohibitive designs and that it was necessary practically to double this. This means that the field coils also have six to eight volts per turn generated in them. The total number of field turns must, therefore, be very small in order to keep down the field electromotive force, for this represents simply a choke-coil in series with the armature. If the armature counter electromotive force should be 200 volts, for instance, which is rather high in practice with 25-cycle motors, then a field self-induction of half this value would allow about 14 turns total in the field winding. Compare this with direct-current motors with 150 to 200 field turns for 550 volts, or 60 to 80 turns for 220 volts. The alternating-current 25-cycle motor, therefore, can have only about 20% to 25% as many field turns as the ordinary direct-current motor. This fact makes it particularly hard to design large motors where there must be many poles. In the single-phase motor the induction per pole being limited by the permissible short-circuit voltage, it is necessary to use a large number of poles for heavy torques; but the total number of field turns must remain practically constant on account of the self induction, while in reality the number of turns should be increased as the number of poles is increased. With a given number of poles we may have just sufficient field turns to magnetize the motor up to the required point; but if a large number of poles should be required, then we at once lack field turns and must either reduce the field induction, and thus reduce the output, or must add more field turns and thus get a higher self-induction or choking action in the field, with a consequent reduction in power-factor. Here is where a lower frequency comes in to advantage, for, as I showed before, with the same relative inductive effect, the field turns can be increased directly as the frequency is decreased. The use of 15 cycles thus permits 67% more field turns than 25 cycles and raises our permissible magnetizing limits enormously. This problem is encountered particularly in gearless locomotive motors of large capacity. For increased capacity the driving wheels are made larger, thus permitting a larger diameter of motor, the length, axlewise, being fixed. But with increased diameter of drivers, the number of revolutions is decreased for a given number of miles per hour. With 25-cycle motors we soon encounter the above mentioned limiting condition in field turns; beyond this point the characteristics of the motor must be sacrificed, and even doing this we soon reach prohibitive limits. By dropping the frequency to 15 cycles, for instance, we change the whole situation. The induction per pole can be increased and the number of poles, if desired, can also be increased. The practical result is that, in the case of a high-speed passenger locomotive with gearless motors, a 700-h.p. 15-cycle motor can be got in on the same diameter of drivers as required for a 500-h.p. 25-cycle motor. Also a 500-h.p. 15-cycle motor goes in on the same drivers as a 360-h.p., 25-cycle motor. At the same time these 15-cycle motors have better all round characteristics than the 25-cycle machines as regards efficiency, power-factor, starting, over-load commutation, etc.

Returning to the design of the motor, there is one other electromotive force of self induction which may be considered; namely, that generated in the armature winding and in the opposing winding in the pole face, usually called the neutralizing or compensating winding.

Fig. 4 shows a section of the field and armature corresponding to the usual direct-current motor, or an alternating-current motor without compensating winding. In the direct-current motor the armature ampere-turns lying under the pole face tend to set up a local field around themselves, producing what is known as cross-induction. This produces no harmful effect except in crowding the field induction to one edge of the pole, thus shifting the magnetic field slightly and possibly affecting the commutation in a small degree. But if the armature is carrying alternating current this cross flux will generate an electromotive force in the armature winding, and this will be added to the field self-induction, thus increasing the self-induction or choking action of the machine. As the armature turns on such motors are much greater, in proportion, than the field turns, it is evident that the ampere-turns under the pole face can exert a relatively great cross-magnetizing effect. This high cross-magnetization generates a high armature self-induction which may be almost as much as the field self-induction. Further, this great cross-induction would tend to shift the magnetic field quite appreciably, thus affecting the commutation to some extent.

To overcome this serious objection, the neutralizing winding is added. This is a winding embedded in the pole face and so arranged that it opposes the armature cross-magnetizing action. The arrangement is shown in Fig. 5. As it opposes and thus neutralizes the cross-induction set up by the armature winding, it eliminates the self-induction due to the cross-magnetization. It also prevents shifting of the magnetic field and thus eliminates its injurious effect on commutation. As the cross-flux is practically cut out the armature winding becomes relatively non-inductive. There is, however, a small self-induction in the armature and neutralizing windings, due to the small flux which can be set up in the space between the two windings, they being on separate cores with an air-gap between.

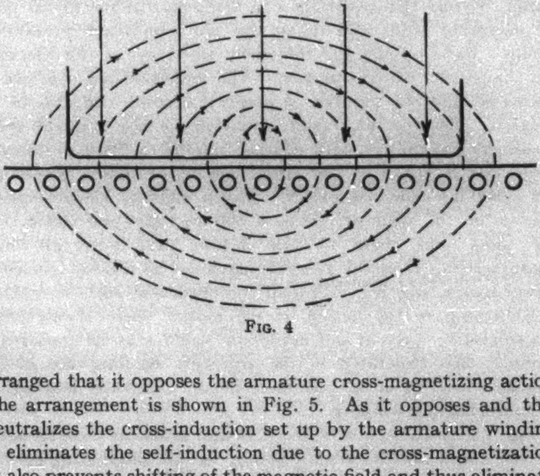

FIG. 4

I have stated that the field turns of the alternating-current motor can be only 20% to 25% as many as in ordinary direct-current practice. It may be questioned how the field can be magnetized with so few field turns. This has been one of the most difficult problems in the motor. Obviously, one solution would be the use of a very small air-gap, but in railway practice there are objections to making the air-gap unduly small. Furthermore, if the armature has large open slots, as shown in Fig. 6, experience shows that a reduction in the clearance between the armature and field iron does not represent a corresponding decrease in the effective length of the air-gap, due to the fact that the fringing of the magnetic flux from the tooth tip of the pole face changes as the air-gap is varied. The most effective construction yet used consists in making the armature slots of the partially closed type as in the secondary of an induction motor. This is shown in Fig. 7.

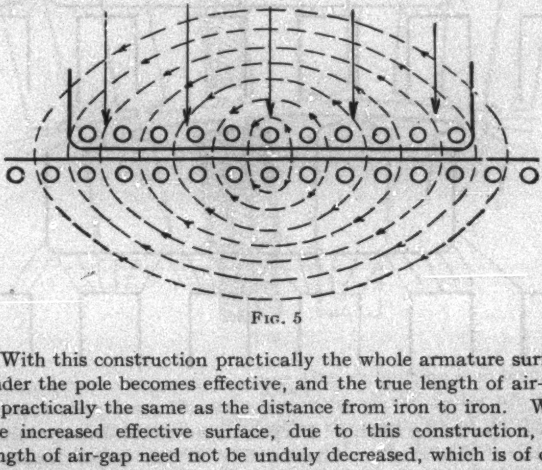

Fig. 5

With this construction practically the whole armature surface under the pole becomes effective, and the true length of air-gap is practically the same as the distance from iron to iron. With the increased effective surface, due to this construction, the length of air-gap need not be unduly decreased, which is of considerable importance in railway work.

A further assistance in reducing the required field turns is the field construction used in the single-phase motor. The magnetic circuit consists of laminations of high permeability and usually without joints across the magnetic path. The iron is also worked either below the bend in the saturation curve or, at most, only slightly up on the bend, except in the case of very low frequency motors where more field turns are permissible.

Taking the whole magnetic circuit into account, on 25-cycle motors about 80% of the whole field excitation is expended in the air-gap, while in direct-current motors, even with a much larger air-gap, as much as 40% to 50% of the magnetization may be expended in the iron and in the joints.

This armature construction with the partly closed slots has been found very effective in large, slow-speed, single-phase motors in which a relatively large number of poles is required. This construction is used on the New Haven 250-h.p., 25-cycle motors; also on the 500 h.p., 15-cycle motor on the Pennsylvania locomotive exhibited at Altantic City at the Street Railway convention, last October. Geared motors for interurban service can be constructed with ordinary open slots with bands, and many have been built that way. The semi-closed slot, however, allows more economical field excitation.

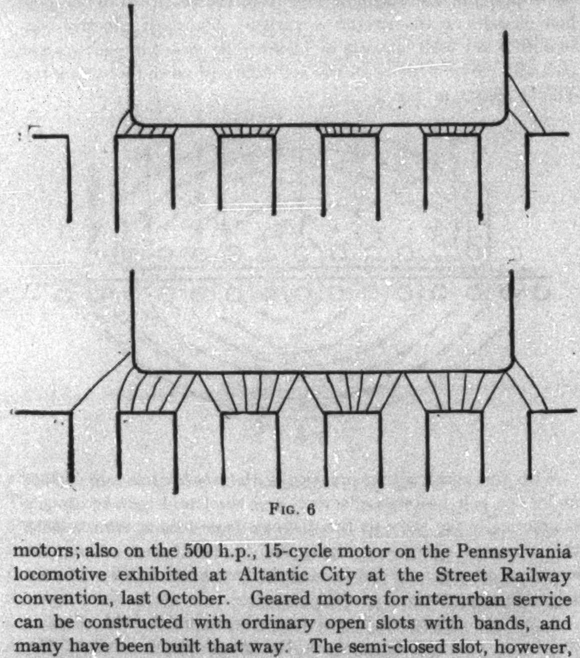

FIG. 6

It may be asked what the objection is to low power-factors on single-phase railway motors, aside from the increased wattless load on the generating station and transmission circuits. There is an objection to the low power-factor in such motors, a very serious one. This lies in the greatly reduced margin for overload torque in case the supply voltage is lowered. In railway work it is generally the requirement of abnormal loads or torques which causes a reduction in the line voltage; that is, the overload pulls down the trolley voltage just when a good voltage condition is most necessary. This is true of direct current as well as alternating current. In the direct current motor, however, such reduction in voltage simply means reduced speed but in the alternating current motor the effect may be more serious.

To illustrate, assume a motor with a power-factor of 90% at full load. The energy component of the input being 90%, the inductive component is about 44% or, putting it in terms of electromotive force the inductive volts of the motor are 44% of the terminal voltage. Neglecting the resistance of the motor, a supplied electromotive force of 44% of the rated voltage would just drive full-load current through it and develop full-load torque. With full voltage applied the motor could develop from five to six times full-load torque. Under abnormal conditions a drop of 30% in the line voltage would still give sufficient voltage at the motor terminals to develop two and one half to three times full-load torque. Let us next take a motor of 80% power-factor at full load. The inductive voltage would then become 60% of the terminal voltage, and therefore 60% of the rated voltage must be applied to send full-load current

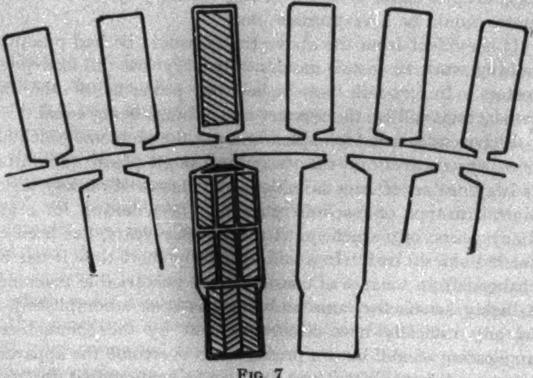

FIG. 7

through the motor. This neglects the resistance of the motor, which, if included, means that slightly more than 60% of the voltage is required. With full voltage applied, this motor would develop about three or four times the rated torque. With 30% drop in the line voltage the motor could develop from one and one half to two times rated torque, which is hardly enough for an emergency condition.

Taking, next, a motor with 70% power-factor at full load it would require 70% of the rated voltage to send full-load current through the motor; with 30% drop in line voltage the motor could just develop full-load torque, and even with 15% drop it would develop only about one and one half times torque. As 15% drop is liable to occur on any ordinary system, this latter motor would be a very unsafe one.

It is evident from the above that it would be bad practice in railway work to install motors with very low full-load power-factors. In general, the higher the power-factor the more satisfactory will be the service, other things being equal.

I have endeavored to explain some of the problems which have been encountered in the design of single-phase commutator railway motors of sizes suitable for all classes of railway service. Here is a type of machine which has been known for a great many years, but which, until the last few years, has been considered utterly bad. In a comparatively short time it has been changed from what was considered an unworkable machine to a highly satisfactory one and this has been accomplished, not by any radically new discoveries, but by the common-sense application of well known principles to overcome the apparently inherent defects of the type. As an indication that the motor is making progress in the railway field, I will mention that the first commercial single-phase railway motors have not been in use more than four or five years, and yet at the present time there have been sold by the various manufacturers in this country and Europe, a total capacity of approximately 200,000 to 250,000 h.p., a very considerable part of which has been put in operation. Considering that the motor was a newcomer in a well established field, the above record is astonishing. However, it may be safely predicted that what has been done in the last five years will hardly make a showing compared with what will be done during the next five years, for the real field for such motors, namely, heavy railway work, has hardly been touched.

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# THE NON-SYNCHRONOUS GENERATOR IN CENTRAL STATION AND OTHER WORK

BY W. L. WATERS

That an induction motor could act as a generator and return power to the line when driven at a speed above that of synchronism, has been known for many years. It has, however, always been regarded as more or less of a scientific curiosity, and except in the case of the Swiss three-phase mountain roads, where the motors are sometimes allowed to run as generators to brake the train on descending heavy grades, the non-synchronous generator has had but few commercial applications. The fact that the characteristics of this generator are such that it must receive a lagging current from the system, the magnitude of which is for a given machine definitely decided by the slip of the generator above synchronism, combined with the fact that when connected to a circuit is has no definite voltage and frequency of its own, make it lack the flexibility of the synchronous generator. In 1895, Mr. B. G. Lamme proposed running a non-synchronous generator with an unloaded synchronous motor, the generator to supply the watt component and the motor the wattless component of the current in the system. But though this suggestion rendered the non-synchronous generator a practical machine, it is easily understood that on account of the lesser flexibility when compared with the synchronous generator, it has not appealed to the central station engineer as a desirable addition to his equipment.

The question as to the advisability of adopting the non-synchronous generator for power station work, was decided adversely by engineers at the time when steam engines and water turbines were the only practical prime-movers. But to-day we have to deal with steam turbines and gas engines, and the coming of these two new types of prime-movers has altogether changed the situation in regard to the use of this generator for power station work. It often happens in such cases that the real meaning and possibilities of the introduction of types of machinery with such fundamentally new characteristics as the steam turbine and gas engine, are not recognized until they are accidentally forced upon us. This has been the case in the present instance; the question of the use of non-synchronous generator with steam turbines was not seriously considered until it was brought up indirectly. In 1904 a copper smelting and rolling company was installing a 1200-kw., 200-volt, direct-current generator for

FIG. 1—Non-Synchronous generator installed at a copper-smelting and rolling mill.

electrolytic work. It was desirable to continue the good steam economy on variable loads, the small floor space and reduced maintenance of the steam turbine, and at the same time to generate 200-volt direct current. A 1200-kw., 6000-ampere, 200-volt, 1800-rev. per. min., direct-current turbine generator was not considered practical, and a non-synchronous generator together with a synchronous converter was suggested as an alternative. It was finally decided to adopt this type of equipment, and a 1200-kw., six-phase, 140-volt, 30-cycle, 1800-rev. per min. generator together with a 1200-kw., six-phase, 150-rev. per min. converter was installed to supply the required 6000 amperes direct current at 200 volts. A direct-current exciter for the converter was provided, so that the direct voltage could be varied from 100 to 230 volts without any danger of instability. The exciter is compound-wound to give constant voltage on the direct-current side of the converter, and the power-factor gradually rises from about 25% at no load to about 96% at full load. When starting up the set, the converter is run up to speed from an auxiliary source of direct current, and the generator by its turbine. They are then thrown together, the generator driving the converter as a synchronous motor, and the converter supplying the magnetizing current of the generator. The governor of the turbine decides the frequency of the set, and the slip of the converter behind the generator is proportional to the load, being about 1% at full load. This equipment has been running now for about three years and operates perfectly. The generator is similar in arrangement to the old open-type turbo-generator, and in consequence is rather noisy, but with the modern enclosed type of generator it is possible to arrange the air circulation better, and to obtain as a result a much quieter running machine.

This installation is given in detail, as it is one instance where the adoption of this apparently inflexible type of generator resulted in an installation, which combines the flexibility of the standard direct- or alternating-current generator with the capacity for heavy overloads of the synchronous converter, and the reliability and robustness of construction of the non-synchronous generator. No other electrical equipment which could have been installed would have given the good results that were obtained. And though the existing conditions rather forced the choice of the equipment in this case, the results so thoroughly met expectations, that engineers began to consider whether the development of the last few years in regard to prime-movers had not changed the non-synchronous generator from a scientific curiosity, to a generator possessing great advantages for certain conditions of power station work.

*General characteristics of the non-synchronous generator.* As most engineers are more familiar with the characteristics and performance of the induction motor than they are with those of the commercial non-synchronous generator, it will be well to show how the characteristics of the two machines are allied. An induction motor of given characteristics carrying a certain definite load, runs at a fixed speed relatively to that of synchronism, and it takes a current the magnitude and phase of which are definite. The torque exerted by the motor is proportional to the product of the current induced in the short-circuited secondary, and the magnetic flux. The electromotive force and the current induced in the secondary, and hence the torque, are proportional to the rate at which the secondary conductors cut the primary magnetic field, that is, to the slip of the rotor above or below the speed of synchronism. As the speed of the motor gradually rises to that of synchronism, the current in the secondary, and the torque gradually fall, till at the speed of synchronism they both become zero. If the speed of the machine still continues to increase, the secondary conductors cut the primary flux in the reverse direction, and the induced electromotive force, the secondary current, and the torque become negative; that is, the machine requires mechanical power to drive it above the speed of synchronism. The machine now returns electrical power to the circuit, and has become a generator. When running as a motor, the current is never in phase with the impressed voltage, for two reasons: (1), the motor requires a certain wattless magnetizing current; and (2), the motor windings, both primary and secondary have a certain amount of self-induction. This makes the current lag behind the impressed voltage by an angle $\phi$, depending on the characteristics of the machine, and on the load it is carrying. When the machine runs above synchronism as a generator, it still takes from the circuit the wattless magnetizing current, and the circuits still possess their self-induction. And as the watt component has reversed in direction, this will mean that the primary current lags less than 180° behind the voltage impressed by the circuit on the generator, hence the current leads the electromotive force supplied by the generator to the circuit. Thus we have as a fundamental characteristic of the non-synchronous generator, that for a given load it runs at a certain definite speed above that of synchronism, and that, (*a*) it supplies a watt current which represents the power delivered by the generator to the circuit, and (*b*) it takes a wattless magnetizing current from the system, the magnitude of which depends on the voltage and on the watt component of the current. Hence this type of generator cannot supply a lagging current to the outside circuit, and can only deliver power to a circuit which can provide the lagging magnetizing current required by a non-synchronous generator: for any given speed, the magnitude and phase of the current which the generator will supply is definitely fixed. Also as the wattless component of the current varies in magnitude when the load of the machine changes, we must have in circuit some apparatus which can supply a variable amount of lagging current, and which will keep the voltage of the circuit constant. It is these apparently rigid and inflexible conditions which have prevented any extensive use of the non-synchronous generator, and it is only because under certain modern conditions these limitations do not mean serious disadvantages, that this generator is now put forward as an important part of a power station equipment.

Usually the load on a power station is either non-inductive or has a lagging power-factor, so that if this type of generator is used, the lagging current required by the generator, and perhaps also by the outside circuit, must be artificially supplied. There are two ways of obtaining the lagging current required by the non-synchronous generator: (1), from a condenser; (2), from a synchronous generator or an over-excited synchronous motor. It would not be desirable commercially, to install a condenser specially to supply the required lagging current, as the cost would be prohibitive; but a large cable system has quite a considerable electrostatic capacity, and the lagging current supplied by this system will usually help greatly in reducing the size of the necessary synchronous machine. In any case, however, it is necessary to have a synchronous machine, either a motor or a generator, in the circuit, in order to set the frequency and the voltage. If we have the non-synchronous generator running together with a synchronous generator, the latter machine supplies all the lagging wattless current required by the non-synchronous generator and the outside circuit, while the voltage of the circuit is decided by the excitation of the synchronous generator. The distribution of the watt component of the current between the two machines, is decided by the governors of the prime-movers. The load which the non-synchronous generator takes, depends on the percentage slip by which it leads the synchronous generator, and the remainder of the load is taken by the synchronous generator. When additional load comes on the station, it first comes on the synchronous generator, and then, as this machine slows down and allows the slip of the non-synchronous generator to increase, part of the load is transferred to this latter machine. In any case, the voltage regulation of the system is that of the synchronous generator, and the voltage of the circuit under any condition of load is decided by the excitation of this machine. If we have the non-synchronous generator running together with a synchronous motor or synchronous converter, then the same remarks apply. The voltage regulation is that of the synchronous machine, and the voltage of the circuit is decided by the magnitude of its excitation. When the load increases, the additional load comes first on the synchronous machine, energy being supplied to the system from the momentum of its rotating part, and then as the machine slows down a little, the load is transferred to the non-synchronous generator, the synchronous machine supplying simply the additional lagging current required by the generator when carrying the additional load. The synchronous machine supplies at all times all the lagging wattless current in the circuit, and the governor of the prime-mover driving the non-synchronous generator, decides the frequency of the circuit, the synchronous machine slipping behind the generator an amount just sufficient to allow this latter machine to supply all the power required by the circuit.

*Non-synchronous generators in power station work.* Obviously the disadvantage of the non-synchronous generator for power station work is, that it cannot carry a lagging wattless current, that it requires an additional lagging wattless current to excite it. The power-factor of the current supplied by such a generator is a direct measure of the amount of wattless current required to excite it under that particular load. The power-factor which can be obtained in designing any non-synchronous generator, depends on the size, speed, voltage, and frequency of the machine. Low speed, high voltage, and high frequency, all tend to lower the power-factor which can be obtained.

Table 1 gives the characteristics of steam-turbine and gas-engine-driven non-synchronous generators of from 1000 kw. to 10,000 kw. for 2200 and 13,200 volts, and for 25 and 60 cycles. The table shows that on high-speed 2200-volt generators, the power-factor rises as high as 98.25 per cent. and that we can obtain on such machines a power-factor which averages 97% to 98% from one-half to one and one-quarter load, while the no-load magnetizing current is less than 10% of the full-load current of the machine. This being the case, the fact that these generators require a wattless current to excite them, ceases to be a serious objection, and it is seen that the one important limitation of this type of machine is, that it cannot supply lagging wattless current to the outside circuit. Of course the low-speed, 60-cycle machines, are relatively poor as regards power-factor and exciting current, so that the use of non-synchronous generators would not be advocated under these conditions, unless their other characteristics made them particularly advantageous for the conditions under which they were to be used. It will also be seen from Table 1 that another advantage of this type of

TABLE I

25 CYCLE—TURBO-ALTERNATORS

| Kilowatts | Rev. per min. | Volts | LOAD | | | | | | No-load current | Slip |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 0.75 | 0.50 | 1 | 0.75 | 0.50 | | |
| | | | Efficiency | | | Power-factor | | | | |
| 1000 | 1500 | 2200 | 97.6 | 97.7 | 97.5 | 97.0 | 97.5 | 97.0 | 8.3% | 0.75% |
| | | 13000 | | | | 95.0 | 95.9 | 96.5 | | |
| 2500 | 1500 | 2200 | 98.2 | 98.2 | 97.9 | 97.9 | 97.3 | 96.4 | 8.3 | 0.48 |
| | | 13000 | | | | 96.5 | 96.9 | 96.0 | | |
| 5000 | 1500 | 2200 | 98.3 | 98.2 | 98.0 | 98.0 | 97.7 | 97.4 | 8.5 | 0.46 |
| | | 13000 | | | | 96.5 | 97.0 | 96.5 | | |
| 10000 | 750 | 2200 | 98.5 | 98.4 | 98.2 | 98.2 | 98.0 | 97.5 | 8.1 | 0.40 |
| | | 13000 | | | | 96.8 | 97.3 | 97.1 | | |
| 60 CYCLE—TURBO-ALTERNATORS | | | | | | | | | | |
| 1000 | 1800 | 2200 | 97.6 | 97.7 | 97.5 | 96.4 | 96.9 | 96.4 | 9.5 | 0.75 |
| | | 13000 | | | | 94.0 | 95.0 | 94.5 | 11.5 | |
| 2500 | 1800 | 2200 | 98.2 | 98.2 | 97.9 | 97.2 | 96.8 | 96.2 | 9.5 | 0.48 |
| | | 13000 | | | | 94.5 | 95.3 | 94.8 | | |
| 5000 | 1200 | 2200 | 98.3 | 98.2 | 98.0 | 96.0 | 97.2 | 97.0 | 9.5 | 0.45 |
| | | 13000 | | | | 94.5 | 95.6 | 95.5 | | |
| 10000 | 720 | 2200 | 98.5 | 98.4 | 98.2 | 97.6 | 97.6 | 97.1 | 9.5 | 0.40 |
| | | 13000 | | | | 95.3 | 95.6 | 95.5 | | |
| 25 CYCLE—GAS-ENGINE-DRIVEN ALTERNATORS | | | | | | | | | | |
| 1000 | 94 | 2200 | 96.7 | 97.1 | 97.2 | 94.0 | 94.2 | 92.0 | 16.5 | 1.5 |
| | | 13000 | | | | 89.3 | 90.9 | 88.7 | 18.0 | |
| 2000 | 83 | 2200 | 97.0 | 97.4 | 97.6 | 95.5 | 95.1 | 94.0 | 16.5 | 1.4 |
| | | 13000 | | | | 92.4 | 93.2 | 90.7 | | |
| 3500 | 75 | 2200 | 97.1 | 97.5 | 97.7 | 95.7 | 95.2 | 94.2 | 16.5 | 1.4 |
| | | 13000 | | | | 92.6 | 93.4 | 91.0 | | |
| 60 CYCLE—GAS-ENGINE-DRIVEN ALTERNATORS | | | | | | | | | | |
| 1000 | 3 | 2200 | 95.5 | 95.7 | 96.0 | 88.8 | 88.5 | 84.6 | 25.0 | 1.8 |
| | | 13000 | | | | 83.0 | 81. | 73.3 | 40.0 | |
| 2000 | 82 | 2200 | 96.0 | 96.3 | 96.5 | 89.5 | 89.2 | 85.6 | 24.0 | 1.7 |
| | | 13000 | | | | 83.5 | 81.8 | 75.0 | 38.0 | |
| 3500 | 75 | 2200 | 96.3 | 96.5 | 96.7 | 90.8 | 89.5 | 87.0 | 22.5 | 1.6 |
| | | 13000 | | | | 85.0 | 83.3 | 77.0 | 35.0 | |

generator, is the extremely high efficiency at all loads that is obtained in high-speed machines. This means that these generators have a very low temperature rise at normal rated load, and that they have a very large overload capacity. The normal ratings of the individual machines given in the table were chosen so that their characteristics would be best at from one-half to one and one-quarter rated load. All the machines given, can generate from two and one-half to five times their rated output, and as far as general characteristics are concerned could be rated up 50%. It was stated above, that the slip of the non-synchronous generator relatively to the synchronous generator, must increase from no load to full load, in order that the former may carry its due share of the load. So if we wish the load always to be automatically divided between the two machines, we must adjust the governor of the synchronous prime-mover so that its drop in speed from no load to full load, equals the drop in speed of the non-synchronous prime-mover plus the full-load slip of the non-synchronous generator. This means that the speed and frequency of the synchronous generator must change with the load, but we see from the slip given in the table that this change is unimportant. The slip varies from 0.4 per cent. to 0.75 per cent. in high-speed machines and from 1.4 per cent. to 1.8 per cent. in low-speed machines, and this is about as close as the governors will regulate in any prime-mover.

The greatest commercial field for the non-synchronous generator, is undoubtedly in connection with turbine-driven generators. This type of generator is more suitable both mechanically and electrically for high-speed work than any other type of electrical machine. The squirrel-cage secondary with heavy copper bars, each bar held in a separate closed slot, and practically requiring no insulation, is an ideal construction mechanically, and is one which can be operated at very high temperature without damage. Comparing this with the rotating magnets of the standard synchronous turbo-alternator, the difference is very great. The magnet winding of a synchronous turbo-alternator consists of a number of turns of thin strap separated by insulation. The windings often reach high temperatures due to overload at low-power-factors, and are subject to heavy centrifugal stresses and a potential difference of 125 volts to ground. We can see that such a construction does not compare with that of the squirrel-cage rotating secondary of a non-synchronous generator. And as a breakdown on the field of a synchronous turbo-generator usually puts the machine out of commission for a couple of weeks, we can see the mechanical advantages possessed by the non-synchronous generator. The simplicity in construction and insulation of the rotating parts, the ease with which the centrifugal stresses necessarily present can be taken care of, and the absence of a complicated winding and brush gear, necessarily tend to reduce the cost of the non-synchronous generator compared with that of the standard synchronous generator. Of course the actual cost of any machine depends on the performance specification to which it is designed, and on how closely the machine is rated, but it can readily be seen that the non-synchronous generator offers facilities for cheaper design and manufacture which are not presented by the synchronous generator.

*The excitation of the non-synchronous generator.* A synchronous generator requires direct-current excitation, while a non-synchronous generator requires alternating excitation. The non-synchronous generator is excited by a lagging current taken usually from a synchronous machine, and as this synchronous machine requires direct-current excitation to produce this lagging current, it can be said that indirectly the non-synchronous generator does require a direct-current exciter. But on account of the small air-gap of this type of generator, it requires much less excitation than a synchronous generator. The actual capacity of the exciters which are required by a power station consisting of non-synchronous generators, depends on the power-factor of the load on the system. The capacity required will usually vary from one-quarter to one-half of that which would be required for the corresponding synchronous generators. Of course if we have a cable system with high electrostatic capacity, this will supply part of the required lagging excited current and will reduce the size of the required exciter. The charging current of the New York Interborough system is given as about 105 amperes at 11,000 volts; that is, about 2000 kilovolt-amperes, and that of the New York Edison system is about 40 amperes at 6600 volts; that is, about 450 kilovolt-amperes. We see from Table I that the capacity-charging current of the New York Edison system is sufficient to supply full-load magnetizing and wattless current required by a 2000-kw. 6600-volt, 25-cycle turbo-driven non-synchronous generator when running on a non-inductive external load. In the same way the capacity-charging current of the Interborough system would be sufficient to supply the wattless current of a 10,000-kw. 11,000-volt, 25-cycle turbo-driven generator. If we had a cable system such as the Interborough distributing at 20,000 volts, we would have a charging current of 190 amperes at 20,000 volts, which would be sufficient to supply the wattless component for 40,000 kw. in 22,000-volt, 25-cycle turbo-driven non-synchronous generators.

So we can see that the electrostatic capacity of a large cable system will play an important part when we come to consider the introduction of such generators into some of the large New York power stations.

In a system consisting of non-synchronous generators supplying power to synchronous converters, it is unnecessary to have any exciters or synchronous machines in the power station. The first converter put in circuit, must be run up to speed from the direct-current side, and then thrown on the generator circuit, when it will excite the latter, and the voltage will be decided by the excitation of the converter. We can see from Table I that the power-factor of a non-synchronous generator can be made to remain practically constant from one-half to one and one quarter load. This means that the amount of wattless lagging current taken by the generator throughout its normal working range, will be practically proportional to the watt current. Hence assuming that we can neglect the capacity-charging current of the cable system, if we have a number of converters running on the circuit, we can adjust the shunt excitation of each converter so as to give the correct voltage at no load, and the series excitation can be adjusted to obtain any desired voltage-characteristic as the load comes on the system, the converters compounding the generators by their series winding. This compounding of the generators as the load comes on any sub-station, affects of course all the other sub-stations fed from those generators; so if we are not regulating for constant voltage, it may be advisable in some cases to introduce artificial self-induction into the converter feeder circuits so as to over-compound these circuits rather than the generators, and avoid disturbing the voltage on other unloaded sub-stations. In a large system, the capacity current of the cables can not be neglected, so the wattless current to be supplied by the converters will not be directly proportional to the load. Such a system usually requires constant voltage at the direct-current terminals, and in such cases it may be found advantageous to install compound-wound converters with automatic voltage regulators to control the shunt excitation. The voltage regulators would then serve to control the voltage of the generators, and to keep that constant, while the series winding would serve to compound each individual feeder in order to compensate for the voltage-drop in that feeder. In such a system, all the regulators controlling the voltage on a given group of generators would be tied together, so that any one regulator could not act before, or act against the others, and make the shunt excitation of the individual converters different.

If there is no electrostatic capacity in the system, the power-factor of the converters is practically the same as the power-factor of the generators; but if there is capacity in circuit which helps to supply the lagging current, then the power-factor of the converters will be higher than that of the generators. Taking once more the Interborough system, and assuming there are 75,000 kw. of 11,000-volts turbo-driven non-synchronous generators in the power station, and 75,000 kw. in synchronous converters in the sub-station, then the capacity current supplies 13 per cent. of the wattless current taken by the generator on full load, and we have a full-load power-factor for the converters of 98 per cent. Such a power station of non-synchronous generators, having no direct-current exciters and exciting circuits, is much simpler as regards cables and switchboard connections than a similar station with synchronous generators, and is much simpler to operate. There is no necessity for synchronizing the generators; they are simply run up to speed and are then thrown on the line in series with a reactive-coil, (to limit the rush of current). The reactive coil is then short-circuited, and the generators are automatically excited from the converters and take care of themselves. The governors of the prime-movers are controlled by pilot motors from the switchboard, and the load can be distributed at will among the different generators without adjusting the excitation to keep the power-factor constant, as would be necessary with the synchronous generator. This gives an ideally simple station, as there are no auxiliary circuits, and the switchboard is practically limited to the main generator and feeder switches and instruments.

*Short-circuits and resonance.* During the last few years we have heard a great deal regarding resonance and high power surges in large installations with distributing cable systems of high electrostatic capacity. We can investigate these phenomena mathematically in detail, if we choose to make a number of more or less arbitrary assumptions, but it is the author's opinion that at present we are only justified in describing these phenomena in general terms. By a high-power surge is meant the oscillation sometimes set up in a system by a sudden rush of current, such as a short-circuit, and which has usually the fundamental frequency of the circuit. The power represented by the surge, is proportional to the square of the value reached by the current in the first sudden rush, and the rise in voltage is directly proportional to the surge of the current. Resonance effects, cover the extremely high rises of potential which take place in a circuit containing self-induction and capacity, when the frequency of the circuit has a certain value depending on the amount of induction and capacity in circuit. In ordinary power systems, resonance cannot generally take place at the normal frequency of the circuit, but there are usually higher harmonics of this normal frequency introduced by distortion of the fundamental wave-form, and there may be resonance and high voltage due to one of these high harmonics.

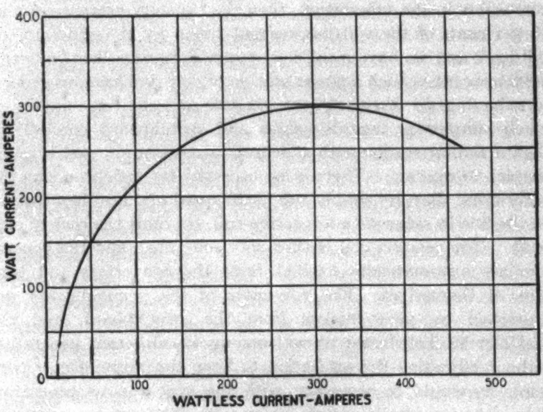

FIG. 2.

This short analysis shows at once why a power station of synchronous generators, is so liable to suffer from surges and resonance. Synchronous generators and motors will give a greater sudden rush of current, or surge, in the case of short-circuit than almost any other class of machine. And though they have wave-forms which approximate closely to sine waves on no load, these wave-forms become so distorted by armature reaction on load, and change so with the magnitude and phase of the current, that there is an excellent chance of introducing such harmonics as will produce resonance. If we were deliberately to try to choose conditions which would be most liable to give trouble from high-power surges and resonance, we could not well choose anything that would be worse than synchronous generators feeding synchronous motors through a cable system of high capacity. The non-synchronous generator is a great contrast to the synchronous generator in this respect, as it tends rather to eliminate disturbances from the line than to originate them. A short-circuit on a system means that the voltage falls to zero, consequently any non-synchronous generator on the circuit becomes dead, and does not tend to supply either power, current, or voltage to the short-circuit. Further, the wave-form of the electromotive force of a non-synchronous generator is virtually a sine wave for all loads, and it has no tendency at all to introduce higher harmonics which might produce resonance. If the synchronous machines supplying the wattless current in the circuit have a badly distorted wave-form, the magnetizing current of the non-synchronous generator will also be distorted, but there will be a strong tendency to damp out all harmonics in the electromotive force wave-form of the system. And we can say that, generally speaking, the non-synchronous generator acts as a strong damper to remove all harmonics in the electromotive force wave-form of the system, introduced by distortion of the wave-form of the synchronous machines. This distortion in a synchronous machine, is due to the armature reaction of the watt component of the current, rather than the wattless, so we see that the best conditions as regards freedom from distortion and harmonics are obtained by the use of a synchronous converter or unloaded synchronous machine, rather than a loaded synchronous generator or motor to supply the wattless current required to excite a non-synchronous generator.

Fig. 2 shows approximately the relation of the watt component to the wattless component of the current supplied by a 2000-kw. non-synchronous generator, the curve being for its normal rated voltage of 11,000 volts; for a different voltage the values of current, both watt and wattless, should be multiplied by the direct ratio of the new voltage to 11,000 volts. We can see from this, that the magnitude of the watt current bears a definite relation to that of the wattless, and that the watt current, and consequently the load on the machine, cannot change without the wattless current also changing. Further, for each point on the curve, the slip of the non-synchronous generator ahead of the synchronous machine has a *certain definite* value. This shows that when a short-circuit comes on a system consisting of a non-synchronous generator and synchronous generator or motor, the short-circuit will come on the synchronous machine. If the voltage drops to zero, the non-synchronous generator will be dead; but if the short-circuit is not severe enough to reduce the voltage of the system to zero, then it may still supply current to the circuit. The amount which it supplies will depend on the way in which the excitation of the synchronous machines is changed by the automatic voltage regulators. But a change in load which can be taken care of by the voltage regulators, hardly comes under the class of short-circuits, and as these latter effects are the only serious ones, we will consider them alone. We see from the above that the non-synchronous generator takes no part in the sudden surge of current which occurs on a short-circuit, so that this surge cannot be greater than that which is supplied by the synchronous machines in circuit.

The sudden surge which takes place when any synchronous machine, whether generator, motor, or converter, is short-circuited is equal to:

$$\frac{\text{Electromotive force of synchronous machine}}{\text{self-induction in circuit}}$$

After the current has flowed for an appreciable time, so that the magnetism of the synchronous machine has had time to change, the armature reaction cuts down the electromotive force generated, and the current falls to the value commonly known as the short-circuited value, this being the value of the current on a continuous short-circuit. The 5000-kw. 11,000-volt Manhattan generators will give a continuous short-circuit current about three times full-load current, but the instantaneous value of the current on a sudden short-circuit is about five times this; that is about fifteen times normal full-load current. If these generators are supplying synchronous converters, these converters will also supply power to the short-circuit. The 1500-kw. Manhattan converters give about full-load current on a continuous short-circuit on the alternating-current side, with the self-induction of the transformers and reactive-coils in circuit, and the instantaneous value on sudden short-circuit is about three times this value. So a short-circuit on a system consisting of the Manhattan generators supplying power to synchronous converters will give, on sudden short-circuit, a rush of current equal to eighteen times the total full-load current of the generators in circuit, while after a short period the value of the short-circuit current will fall to about one-fifth of this value. Assuming now that we had non-synchronous instead of synchronous generators in the power station, the short-circuit current would be limited to that from the converters, and the sudden surge would be equal to three times full-load current. The voltage of the system would fall to zero, and the converters would supply a gradually decreasing current to the short-circuit until their rotational energy was all expended, and they had come to rest. We see then that with non-synchronous generators in the power station, the magnitude of the sudden surge on a short-circuit would be reduced to one-fifth of that which would take place with the present synchronous generators. This means that the voltage-rise would be only one-fifth, and the power of the surge would be only one twenty-fifth. These figures do not need any comment.

There is one point, however, that must be considered when operating non-synchronous generators on the system containing considerable electrostatic capacity, and that is that the individual generator units are not too small. A non-synchronous generator can be excited by the lagging current from a condenser, and the voltage to which it will be excited depends on the size of the condenser. In a system consisting of non-synchronous generators and synchronous machines we might, as the result of opening circuit-breakers by line disturbances, have just one generator and one small synchronous unit left running on the line. The capacity current of the cable system would then tend to build up the voltage of the machines until the saturation of the magnetic circuit prevented any further rise. Taking the 2000-kw. 11,000-volt non-synchronous generator, the current curves of which are shown in Fig. 2, the magnetizing current at 11,000 volts is 9 amperes. If the capacity-charging current of the cables is 100 amperes at 11,000 volts, and the synchronous machine is so small as to take a negligible lagging magnetizing current, it would probably mean that the voltage of the machines would build up to double the normal. If, however, the smallest machine on the circuit were a 10,000-kw. generator, a 1500-kw. synchronous motor or synchronous converter, the rise in voltage would not be more than 10 per cent.; if the minimum size generator unit had been 20,000 kw. there would be no rise in voltage; so that this is a condition which can be taken care of when laying out the station.

Distortion of the wave-form introduces higher harmonics, and may cause resonance or cross-currents. In a synchronous generator or motor, the wave-form of the magnetism is usually badly distorted as the load comes on the machine, this distortion being greater the higher the power-factor, and the greater the load. This distortion of the magnetic wave, introduces higher harmonics into the wave-form of the electromotive force generated in the armature conductors. The most important harmonic introduced is the third; but the fifth, seventh, ninth, and higher harmonics are also usually presented. In a three-phase winding, the third harmonic, and also harmonics of this third harmonic, appear in the electromotive force between the neutral and outer terminals, but not in the electromotive force between the outer terminals. They therefore appear in a three-phase, four-wire system, or in a three-phase system with grounded neutral. The other harmonics appear, no matter what the connections are. Though the presence of these harmonics may not cause harm in any individual case, it is always possible that there may, under certain conditions of circuit and load, be harmonics of a frequency sufficiently close to that of resonance to cause serious rise of potential. And if generators of different characteristics run together, or if there are loads of different magnitude and phase, or different excitation on the synchronous generators or motors, cross-currents are liable to be produced between the machines; this is especially the case in running with a grounded neutral. Synchronous converters are very much better than any other class of synchronous machines as regards distortion of wave-form when operating with unity power-factor; they have practically no armature reaction, and the electromotive force wave generated under such conditions is approximately a sine. So the above remarks on synchronous generators and motors, only apply to synchronous converters to a limited extent.

Non-synchronous generators have no distortion of field due to armature reaction, and so long as the iron in the magnetic circuit is not saturated, the electromotive force wave-form of these generators is virtually a sine wave for all conditions of load. This means that there can be no cross-current between non-synchronous generators, due to difference in wave-form, and that they have no tendency to produce resonance in the circuit. Furthermore a non-synchronous generator acts as the strongest possible damper in a circuit; and if there is any surge, unbalancing of phases, distortion of wave-form or hunting present, the non-synchronous generator will tend to damp it out, and to restore the original condition of steady sine-wave operation. If we then have a system consisting of non-synchronous generators supplying power to synchronous converters, it would be as nearly perfect as possible in its freedom from surges and resonance. The synchronous converter would give the minimum distortion of any synchronous machine, and the non-synchronous generator would tend to damp out any disturbance that occurred on the line. Such a system would certainly be very much superior to the synchronous generators and synchronous motors in regard to liability to disturbances from resonance and surges, and in all probability the engineers of such a system operating with grounded neutral would hardly know that such phenomena existed.

I have endeavored to show that the non-synchronous generator is very much superior to the synchronous generator from almost every point of view, for the purpose of supplying power to motor-generators and synchronous converters through an underground cable system; and that synchronous converters are less liable to introduce line disturbances than synchronous motors. In some cases it might be considered advisable to install both synchronous and non-synchronous generators, or the station might be one in which the units first installed were synchronous generators, and the later extensions were non-synchronous generators In such cases it is readily seen that the advantages as outlined above, are obtained to a degree which depends on the ratio of the number of non-synchronous to the synchronous generators. It should be remembered that the non-synchronous generator and synchronous converter, give the best combination to ensure freedom from line disturbances, and that the synchronous generator and synchronous motor give the worst; combinations of the two systems lie between these two.

*Small power stations.* There have now been considered in detail, large systems which can easily provide the necessary lagging exciting current for the non-synchronous generator, either from the charging current of the cable system or from the synchronous motors or synchronous converters in the system.

With smaller power stations which supply power direct to motor and lighting circuits, the conditions are not so favorable to the non-synchronous generator, as this generator is primarily one for high power-factor loads, and it is at a distinct disadvantage in a station in which the load is of low power-factor. The advantages of the non-synchronous generator as outlined above are, however, so great that each particular case should be considered to see whether it will allow of its use. Usually the load on such a station having low power-factor, consists mainly of motors during the day time, whereas the heavy peak load is the lighting load at night. We can therefore install synchronous generators sufficient to carry the day motor load, and non-synchronous generators to assist in carrying the lighting load at night. Let us take a 60-cycle station with a day load of 2500 kilovolt-amperes which will probably have a power-factor of 70 per cent. and a night load of 4000 kilovolt-amperes with a power-factor of 98 per cent. And assume further that we have two 1250-kilovolt-amperes synchronous turbo-generators to carry the day load, and two 1000-kilovolt-ampere non-synchronous generators to assist in carrying the night load. This night load consists of 3850 watt kilovolt-amperes and 800 wattless kilovolt-amperes, and the two non-synchronous generators require in addition 980 wattless kilovolt-amperes to excite them. We shall then have the two synchronous generators carrying a load of 2500 kilovolt-amperes at 70 per cent. power-factor and the non-synchronous generator carrying a load of 2250 kilovolt-amperes at power-factor 0.98.

It is nearly always more economical to supply wattless current in a power station from unloaded high-speed synchronous motors, than from the main synchronous generators. This is more especially the case with steam-turbine or very slow-speed units, as such machines cannot be economically designed with the good regulation and the margin on the fields necessary to handle properly a low power-factor load. Such a machine to carry satisfactorily a certain kilowatt load at power-factor 70 per cent. will be about double the size of a unit to carry the same kilowatt rating at unity power-factor. In the station considered, we have assumed that the synchronous generators supply all the wattless current required for the non-synchronous generators and outside circuit. It would be better, however, to make the synchronous generators 1000 kilovolt-ampere units with poor regulation, and install also a 1500-kilovolt-ampere high-speed synchronous motor to supply all the wattless current. This should give a cheaper and more flexible installation, as we would be able to run the non-synchronous generators without the synchronous generators at any time, using the synchronous motor to excite them. The non-synchronous generators would require no direct-current exciters, exciting circuits, or switch panels: they would probably be cheaper than the synchronous generators, and would be simpler to handle, and less liable to break down. So we can see they have such important advantages that they should be carefully considered in each individual case before deciding to adopt synchronous generators alone.

*Other applications of non-synchronous generators.* In the above remarks, the non-synchronous generator has been dealt with more especially as a steam-turbine-driven unit for generating alternating current. This type of generator, however, often presents important advantages for other and more especial conditions. Two of the most important of such cases are gas-engine-driven alternators, and steam-turbine-driven direct-current units. The advantage of the non-synchronous generator for gas-engine-driven units, is of course that it does not require the extreme uniformity of speed required by a synchronous generator, and the advantage of its application for direct-current generation by turbine units is, that by the use of a non-synchronous generator and synchronous converter we can avoid the use of a direct-current turbo-generator.

*Gas-engine-driven units.* With modern tandem and twin-tandem gas engines designed along certain well-established lines, giving respectively two and four impulses per revolution, gas-engine-driven alternators can be and undoubtedly are run in parallel. But to obtain satisfactory operation, heavy fly-wheels and heavy dampers on the pole-faces of the alternators are necessary. Considered apart from the engine itself, however, such fly-wheels mean a considerable increase in cost, and sometimes in the floor space taken up by the engine, and also a loss in efficiency due to the increased bearing friction and windage. And there is necessarily a loss in the dampers on the pole-faces of such gas-engine-driven alternators, on account of the irregularity in speed of the gas engine, though this loss would not be detected except in a gas-consumption test, when running in parallel with other units. Instead of synchronous units, we can install non-synchronous generators and have high-speed synchronous motors running light, to provide the necessary lagging current for the outside circuit and for exciting the generators. In this case any change in load comes first on the synchronous motors, causing a change in their speed, and in consequence a transferring of the change in load to the generator. And as the voltage of the generator would be decided by the excitation of the synchronous motors, the voltage regulation of the station is that of the synchronous motors. Hence for constant potential it may be advisable in some cases to control the excitation of all the synchronous motors by one automatic voltage regulator. The size of the direct-current exciter necessary for the synchronous motors would depend on the power factor of the load on the station, and would be greater, the greater the lagging current required by the external circuit. Generally speaking, the size of the exciter required, would be from one-quarter to one-half of that necessary for the corresponding synchronous generators. The probable arrangements would be, a direct-connected exciter on each synchronous motor, which could also be used as a starting motor; and one gas-engine-driven exciter would also have to be installed for starting up the first synchronous motor.

Taking as the load on such a 2200-volt, 25-cycle power station, 20,000 kilovolt-amperes at 70 per cent. power-factor, we would have four 5000 kilovolt-ampere, 75 rev. per min. synchronous generators, each requiring a 125-kw. exciter; or four 3500-kw. 75 rev. per min. non-synchronous generators, together with four 4500 kilovolt-ampere 500-rev. per min. synchronous motors with 60-kw. direct-coupled starting motor-exciters. Each synchronous motor would supply the 1000-kilovolt-amperes exciting current required by one non-synchronous generator, together with 3500-kilovolt-amperes wattless current for the external circuit. The relative efficiencies on the load of 70 per cent. power-factor are as follows:

| | Synchronous generator | Non-synchronous generator and synchronous motor |
|---|---|---|
| Full load | 95.7—(a) | 94.0 |
| 0.75 " | 95.1—(a) | 93.6 |
| 0.50 " | 94.0—(a) | 92.5 |

These efficiencies do not take into account the allowance (a) to be made for additional losses due to the increased friction of the larger fly-wheels, and the losses in the dampers or solid pole-faces which occur with the gas-engine-driven synchronous generator. These additional losses will reduce the efficiency of the synchronous generator below that of the non-synchronous generators set. The cost of the electrical equipment would not be very different in the two cases, and as the larger fly-wheel, shaft, and bearings, required for the synchronous generator would increase the cost considerably, it is probable that the non-synchronous generator equipment would be found a good deal the cheaper. It must be remembered that this is an extreme case, because the low power-factor of 70 per-cent. taken for the outside load is very much against the non-synchronous generator. If the power-factor were higher, the result would be much better.

It might be supposed that unless we had very heavy fly-wheels on the gas engine we would have the same trouble with hunting of the non-synchronous generator and synchronous motor that we would have with the synchronous generator. But such is not the case. There will undoubtedly be cross-currents between the machines, the magnitude of which will depend on the variation in the speed of the gas engine, but it will be practically impossible to break them out of step. The worst effects of this interchange of current between the machines, will be the heating and losses in the armature conductors, and the pulsation in voltage due to the interchange of wattless current. This pulsation of voltage will be diminished by dampers on the pole-faces of the synchronous motor, but it will usually be perceptible when only one generator is running. As these gas-engine-driven units will be used mainly for power work in mills, the slight pulsation of voltage will be unimportant.

Non-synchronous generators are not put forward as the only possible solution of the gas-engine-driven alternator question; but as the most practical, and that which will recommend itself most highly to the conservative power station engineer and manufacturer. It is by no means settled that heavy fly-wheels and powerful dampers are a practical, and advisable solution of the parallel running difficulties.

*Steam-turbine-driven direct-current units.* The other special case for the use of the non-synchronous generator above referred to—the use of such a generator, together with a synchronous converter for the production of direct current—is to meet the special case in which a steam turbine is desired as a prime-mover. Reasons which might compel the choice of the steam turbine are numerous: small overhead space, small floor space, poor foundations, objection to the vibration of reciprocating engines, high steam economy required over a wide range of loads, reduced maintenance and supervision—all these might influence the choice of prime-mover. And as the direct-current turbo-generator, particularly for 250 and 125 volts, has as yet hardly established its position as a conservative and reliable machine, some kind of alternating-current generator would be used in combination with a motor-generator or synchronous converter. Two years ago an electric railway and light company, wished to install an auxiliary 3000-kw. 300-volt direct-current steam-driven generating equipment in the basement of their new public service building. As the head-room was limited to about 12 feet, and as the vibration would be objectionable, reciprocating engines were out of the question. They installed two 1500-kw. horizontal steam-turbine-driven synchronous alternators, and two synchronous motor-generator sets. This would have been an ideal case for a non-synchronous generator and synchronous converter. The converters could be started from the direct-current system, and when up to speed would have excited the non-synchronous generators; no exciters nor exciting circuits would be necessary, the voltage being controlled by the excitation of the converters. The equipment which was installed has a combined full-load efficiency of about 86 per cent. while the combined efficiency of a non-synchronous generator and synchronous converter to do the same work, would have a full-load efficiency of about 95 per cent. In addition it would probably have cost about one-third less.

| | 1000 kw. | 2000 kw. | 3000 kw. |
|---|---|---|---|
| 1. Non-synchronous generator.................... | 97.5 | 98.0 | 98.25 |
| 2. Synchronous converter........................ | 97.0 | 97.5 | 97.75 |
| 3. Combined efficiency of non-synchronous generator and synchronous converter.................. | 94.5 | 95.5 | 96.0 |
| 4. Engine-type generator........................ | 93.5 | 94.25 | 94.5 |

In comparing a turbine-driven non-synchronous generator and synchronous converter, with a steam-engine-driven direct-current generator, the former is found to be a more flexible equipment, one which will carry heavier overloads, and is usually cheaper. We can obtain any compounding desired by means of a compound winding on the converter, and by use of transformers we can have converters of different voltages to supply different direct-current systems. We can place the converter at a distance and transmit the power to it at a high voltage, or we can split up or arrange the equipment as we please. The efficiency is slightly higher on the non-synchronous generator equipment than on the engine-type, as can be seen from the following table of full-load efficiencies for 270-volt generators.

There are many indications that the day of the large engine-type direct-current generators is past. The inaccessibility of the brushes, the difficulty of building and maintaining a commutator of large diameter, and the numerous other drawbacks of this type of machine, have caused it to be regarded as an undesirable addition to a power station. It is a question whether the non-synchronous generator and the synchronous converter are not superior to the engine-type direct-current generator in almost every case, and it should always be carefully considered when a new direct-current station is laid out, or when any extensions are added to existing plants.

FIG. 2

I have endeavored to show that the one great disadvantage of the non-synchronous generator—its inability to carry a lagging wattless current load—should not always prevent its successful adoption, and that the important advantages it possesses in its excellent mechanical construction, high efficiency, good characteristics in regard to short-circuits and resonance, strong balancing and damping action, absence of rotating windings or collector rings, absence of direct-current excitation and exciting circuits, ease of parallel running facility for control of load by governor, and general simplicity and flexibility of operation—all these make it in many cases by far the most advisable machine to adopt. The non-synchronous generator suffers from the fact that it was judged and condemned in the early days of electric power generating stations. At that time there was no real field for this generator, but the introduction of steam turbines and gas engines, and the modern development of large power stations have so fundamentally altered conditions, that the non-synchronous generator is no longer an interesting curiosity, but one of the most promising types of generator for power station equipment. The record of three years in service, places this machine on a demonstrated commercial basis, and while it may have limitations, it possesses so many advantages and its sphere of usefulness is so large, that in the opinion of the author it must be acknowledged to offer greater future possibilities than almost any other type of power station equipment.

## APPENDIX.

The following data on the steam consumption obtained from tests in the copper smelting and rolling plant referred to earlier in the paper, are of interest in comparing the efficiencies of the two types of direct-current generating equipment. The first column gives the actual steam consumption of the 1200-kw. steam-turbine-driven non-synchronous generator and synchronous converter, the turbine being run with 140 lb. steam pressure, 28 in. vacuum and 135 degrees superheat. The second column gives the corresponding figures on a Corliss engine and direct-connected generator, the steam consumption being based on a minimum consumption of 12.5 lb. per indicated horse power at 80 per cent. of full load.

Pounds of steam per kilowatt-hour at direct-current terminals

| Load | Steam turbine equipment | Corliss engine equipment |
|---|---|---|
| 0.5 load | 21.2 lb. | 23.5 lb. |
| 0.75 " | 18.2 | 19.8 |
| 1. " | 17.5 | 20.3 |
| 1.25 " | 17.5 | 23.2 |

*A paper presented at the 225th Meeting of the American Institute of Electrical Engineers, New York, February 14, 1908.*

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# SOME DEVELOPMENTS IN SYNCHRONOUS CONVERTERS

BY CHARLES W. STONE

It is not the intention to make this paper a history of the development of the synchronous converter, but rather to point out some of the more important improvements which have been made in the last few years.

In this country the synchronous converter has become practically an indispensable piece of apparatus, some of the largest lighting and railroad companies being entirely dependent upon it. Abroad the conditions are different, as the motor-generator has been used almost exclusively until within the last few years, when the motor-converter was introduced. The motor-converter is a compromise between the synchronous converter and the motor-generator.

It may be of interest to give at this time some idea of the increase in capacity of these machines in the last ten years on one of the large lighting systems, as this will give some idea of the tremendous development in machines of this type. In 1897, on the particular system in question, there was installed less than 1000 kw. total capacity, and the largest machine was 500 kw.; on the same system in 1907, considerably over 100,000 kw. were in operation, the largest units being 2000 kw.

Most of the larger systems using synchronous converters operate at 25 cycles, but during the last four or five years many systems using 60 cycles have adopted synchronous converters and have found them very reliable.

I think it can be safely said that 60-cycle synchronous converters, even when used for 600-volt railway work where the demands of the service are most severe, can be considered thoroughly reliable and successful, machines as large as 1000 kw. being in successful operation.

The general tendency in the design of synchronous converters has been toward higher speeds, which naturally means reduction in the space occupied by them, lower first cost, less weight etc. All these changes result in smaller buildings, cheaper foundations, and consequently lower fixed charges.

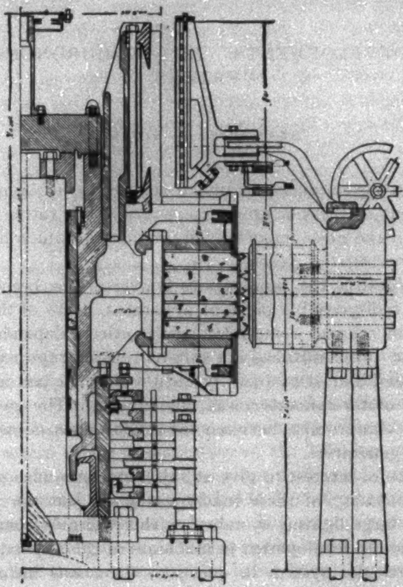

Fig. 1.

As an illustration of the changes that have been made, I shall cite one example. The 2000-kw., 25-cycle, 250-volt synchronous converter as originally designed operated at 115 revolutions and had 26 poles. It occupied a floor space 190 in. by 204 in. and the total weight was approximately 186,000 lb. The newer vertical machine is circular in form, has 18 poles, and operates at 167 revolutions. The diameter is 182 in. and the total weight about 130,000 lb.

*Vertical synchronous converters.* The vertical synchronous converter is so new that it seems advisable to point out some of its essential characteristics. The most novel features are in the shaft and bearings. The shaft, unlike that of the horizontal machine, is stationary; in fact it is nothing but a pedestal supported by and fastened solidly to the foundations. There is only one bearing, which carries the entire weight of the revolving structure. In the first machine built this bearing consisted simply of two cast-iron plates, one of which was fastened to the top of the pedestal and the other being bolted to the spider of the armature. Fig. 1, a cross-sectional view of the machine, shows more clearly this construction. Oil is pumped up through a central hole in the pedestal and forced out between the cast-iron plates, forming an oil-film on which the machine revolves, making virtually a frictionless bearing.

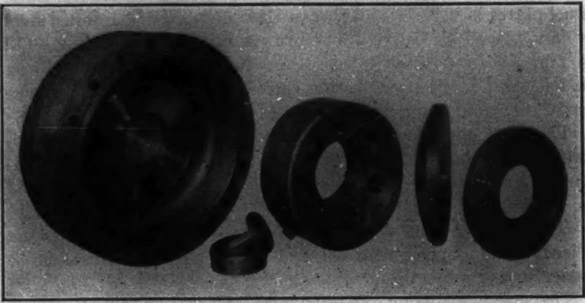

Fig. 2.

In addition to the main bearing, use is made of the entire length of the interior of the spider for a guide bearing. A cast-iron sleeve lined with babbitt is fitted into the spider to form the bearing surface. As the only weight on this bearing is that due to the unbalancing of the rotating structure, the bearing should last indefinitely. The oil, after leaving the top or supporting bearing, passes along the pedestal, (thus oiling the guide bearing) down to the pocket at the base of the machine were it is drained off and used over again. Since the first machine was built, a new type of bearing has been tried which gives promise of success, although only a few months' experience has been obtained as yet.

Fig. 2 shows in general the parts which are used to make up this bearing. The cup-shaped cast-iron piece shown is fastened to the top of the pedestal and forms a seat for the hardened steel bearing plate and carrier, the steel plate being simply doweled in place. Both sides of this plate are accurately ground so that it can be reversed in case of any damage to one surface. It can readily be seen that this construction of the two lower members of the bearing makes it self-aligning.

The top part of the bearing is bolted to the armature spider and is similar to the top of the oil-pressure bearing, except that another hardened steel plate is doweled in place on the under part of this casting to form the wearing surface. Between these steel plates is a bronze carrier with a number of hardened steel rollers placed radially, thus forming the roller bearing. Oil is pumped by a small low-pressure pump to this roller bearing and is drained off after passing through the guide bearing in exactly the same manner as with the oil step.

The stationary part carries the field spools and is split vertically so that the two halves can be drawn apart, making the armature accessible for inspection or repairs. This frame is supported on a number of cast-iron pedestals.

By the above construction it will be noted that the field frame is entirely independent of the rotating structure, making it easier to assemble the machine.

The armature being revolved around the pedestal, it is not possible to obtain any end-play, as in a horizontal machine. Some means must be provided to make the wear on the collector rings equal; this is accomplished by designing the brush rigging in such a manner as to make it possible to stagger the brushes and thus cover the entire width of the collector rings. In addition there are placed on each ring some graphite brushes which act as lubricators.

Fig. 3 is an elevation of the first 2000-kw. machine of the vertical type which has been constructed in this country. By reference to this Fig. it is readily seen how accessible the machine is. It is possible to walk around the machine and see and adjust all the brushes on both the commutator and the collector rings without climbing up on a bearing pedestal or going down into a pit, as would be necessary in a large horizontal-shaft machine. The bearings in the 2000-kw. vertical machine can be taken out, inspected, and replaced in a little over two hours, which would hardly be possible in a horizontal machine of the same size.

The construction above outlined makes it possible to build machines occupying minimum floor space; in fact it has been found possible in stations which have been laid out for 1000 kw., machines, horizontal shaft of the old type, to place a similar number of vertical machines of double the capacity.

*Voltage regulation.* The next matter is that of voltage regulation. With a synchronous converter, as is well known, it is not possible to regulate the voltage on the direct-current side of the machine by means of the field rheostat, as is done with a direct-current generator, without changing the power-factor; for the ratio between the impressed alternating voltage and the direct voltage is fixed by the design of the machine. Hence where voltage regulation is necessary, as for lighting work, charging storage-batteries etc., some means of changing the impressed alternating voltage is necessary.

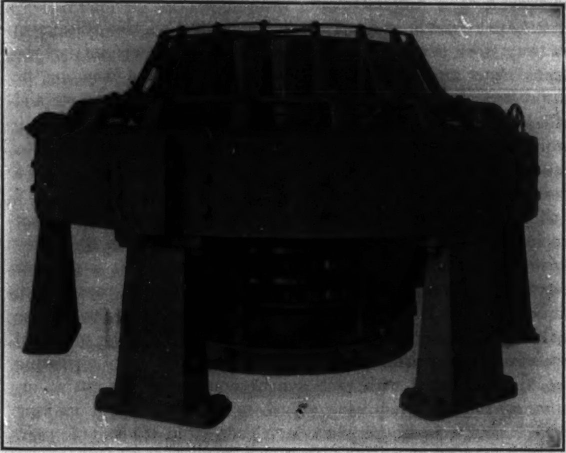

FIG. 3.

A number of different methods have been used to accomplish this result, which I shall describe briefly:

1. On the step-down transformers used with the converter, taps can be placed either on the primary or the secondary side and switches used to transfer from one tap to another. This scheme has many objections and is seldom used now. If the taps are on the primary, oil-switches would have to be used if the voltage were at all high. Such switches would be practically out of the question. If the taps are on the secondary, a dial-switch can be used, but only with the smaller size machines, as it is difficult to build a dial-switch to handle large currents satisfactorily, except at prohibitive expense. This method is also objectionable as it means fluctuation in the lights whenever the switch is moved to a different tap.

2. The common way of obtaining control of the voltage in railway work is to insert in the leads from the secondary of the transformer a reactance, thus furnishing a means of changing the impressed alternating voltage. This method, while simple and effective with the limited ranges in voltage required for such work, would not be applicable for large ranges in voltage. Too much reactance may cause pulsation troubles and it also has a bad effect on the entire system.

3. The arrangement in most general use to-day is to connect an induction regulator between the secondary leads of the transformer and the synchronous converter, by which it is possible to obtain almost any range of voltage within the capacity of the machine. This scheme of operation is in such general use that it is not necessary to describe it in detail. The principal objection to this arrangement is that another piece of operating machinery is used with each synchronous converter outfit, increasing the cost, requiring valuable floor space, and making it necessary to open the secondary leads from the transformer, a serious complication with large low-voltage machines.

4. The next development in this line took place abroad, where an entirely different scheme was used. A few machines of this type have also been built by one of the large manufacturing companies in this country. This method makes use of an alternating-current booster or bucker, mounted on the same base with the synchronous converter. The field has the same number of poles as the converter, and the armature is mounted on the same shaft as the synchronous converter armature. Alternating current is generated in this armature, and can be made to add its voltage to or be subtracted from the impressed voltage, according to the direction

of the excitation. This booster is usually placed between the collector rings and the main armature of the converter, and the taps from the collector rings are connected to equidistant points of the booster armature; similar points on the booster armature are connected to the synchronous converter armature, thus placing the two in series, separate and distinct windings for each phase being used.

The principal objections to such an arrangement are that here again we have an additional operating machine, as in the case of an induction regulator. Extra weight is added to the shaft between its points of support. The ventilation of the converter armature and its accessibility are impaired. Any serious trouble with this smaller machine results in the dismantling of the main synchronous converter in order to repair the small booster.

Another way to construct such a machine is to make it a revolving-field machine, mounting the field on an extension of the shaft beyond the bearing of the collector-ring end of the synchronous converter.

As the armature is stationary, the leads from the secondary of the transformer are led directly to this winding, and from this winding to the collector rings of the synchronous converter. This arrangement has the twofold advantage of being accessible, and not interfering with the ventilation or accessibility of the synchronous converter. This booster can be applied to any standard converter; and being overhung, it is possible to carry a spare machine which can be placed in position quickly and without interfering with the body of the main synchronous converter.

5. The next development is very radical and is unlike any of the other schemes used. It was first proposed by J. L. Woodbridge some time ago. It has been known for some time that the ratio of conversion between the alternating-current and direct-current sides of a synchronous converter could be changed by varying the width of the pole-face. The Woodbridge method makes use of this idea in a very simple and yet effective way.

Fig. 4 shows a two-pole synchronous converter equipped in accordance with this idea. Each field pole is divided into three sections, on each of which are two windings. One of the windings on each section is the main shunt winding, and the other is the regulating winding. All the main windings are connected in series and excited in the ordinary manner. The regulating windings, however, are connected differently. The windings on the two outer sections of all poles are connected in series with one another, and the windings of all the central sections are connected in series with one another, and these two groups are connected in series.

The voltage of the direct-current side of the converter is increased by exciting all the outer sections in a direction to assist the main shunt field, and the middle section an equal amount in opposition to the main field. This condition is shown in Fig. 5. If both these windings are excited in the opposite direction the direct voltage will be lowered. Fig. 6 shows this condition. All that is needed in this arrangement is a field rheostat in the regulating field circuit in addition to the main field rheostat ordinarily used.

The first question that comes up with this scheme is its effect on the power-factor. A number of machines arranged this way have been designed and placed in operation. With these machines the power-factor can be held constant at all loads, yet all the range in voltage desired can be obtained.

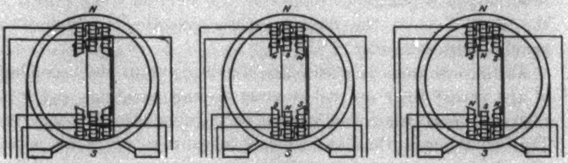

Fig. 4 Fig. 5 Fig. 6

FIGS. 4, 5, 6.

6. Since this method was proposed, another and still simpler method has been brought out. This scheme was proposed by Mr. J. L. Burnham. Instead of making each pole with three sections and with two windings on each, only two sections are used. On each section only one winding is used. The large section corresponds to the main shunt winding on an ordinary synchronous converter, while the regulation is obtained entirely by changing the excitation of the smaller section, exciting it in one direction to boost the voltage, and in the other to lower the voltage.

Anti-hunting devices of many types have been designed and put in operation, most of which have been reasonably successful. The latest, and in many ways the most efficient form of bridge, is formed by placing some copper rods directly through the face of the pole tips, although completely surrounded by the magnetic material. These copper rods are all joined together by heavy copper rings, thus forming a complete squirrel-cage winding similar to that used on the rotor of an induction motor. These rods being placed directly through the pole face are naturally in the main flux, and consequently form very efficient dampers.

Nothing has been said as yet about transformer connections to be used with synchronous converters. There are many conditions existing in different parts of the country which have made it advisable to use some special form of connection for the transformers, but the general practice is to use the diametrical connection with all six-phase machines. This connection is particularly useful in lighting work, as it provides a ready means for obtaining a neutral. With three-phase converters the transformers are usually connected in delta. In many cases they are connected in Y to obtain a neutral, which can be done if special provision is made in distributing the windings in the transformers.

*A paper presented at the 225th meeting of the American Institute of Electrical Engineers, New York, February 14, 1908.*

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# SOME FEATURES OF RAILWAY CONVERTER DESIGN AND OPERATION

BY J. E. WOODBRIDGE

There are now in service in this country in railway work alone, synchronous converters with an aggregate capacity of nearly 1,000,000 kw. In spite of the wide use of this machine, some features of its design and operation are not generally clearly understood, or are quite generally misunderstood. It is the purpose of the following paper to take up three of these features as follows.

*Six-phase versus three-phase converters.* Of the above aggregate capacity, something like one-third consists of machines with six collector rings tapped into the armature winding at six points per pair of poles and termed six-phase converters, although the electromotive forces delivered to them are as truly three-phase as are those delivered to machines with three collector rings. Although it is generally known that the addition of three collector rings to a given three-phase converter reduces the armature $I^2 R$ losses considerably on unity power-factor, it has been heretofore assumed that wattless currents increase these losses of both types of converters by about the same quantity, but not in the same proportion, so that the gain of the six-phase machine is slight on low power-factors.

It has heretofore been shown mathematically, and noted in actual practice, that the armature conductors of a converter nearest the collector ring taps, run warmer than those midway between the collector ring taps. The distribution of the armature $I^2 R$ losses (assuming a winding of uniform cross-section, which is the invariable construction) is shown in the upper part of the accompanying diagram, Fig. 1, the two curves of which represent the theoretical $I^2 R$ loss of a six-ring machine run with the same load, in one case with six-phase, and in the other case with three-phase supply, both at unity power-factor. These curves assume theoretical voltage ratios which are closely approached in practice, but neglect the losses due to unconverted power such as unbalancing, core-loss, incipient hunting, harmonics set up by differences in wave-form, etc., These losses are small, and affect both curves by about the same amount. The vertical scale is given in terms of the heat developed in the same winding

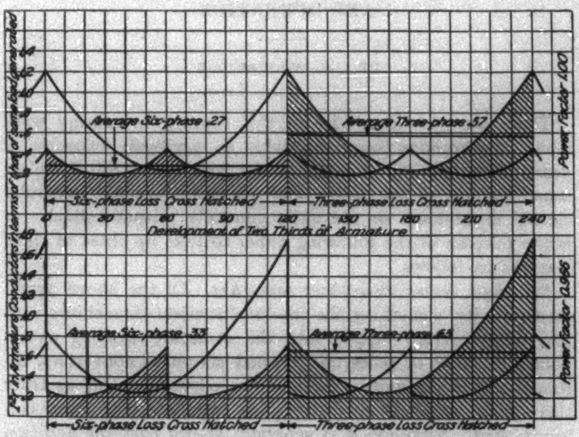

FIG. 1—Distribution of copper losses in armature conductors of converter

when generating the same power in direct current mechanically driven. It will be noted that in this case the operation of the machine as a three-phase converter as compared with its operation as a six-phase converter, increases the average $I^2 R$ loss slightly over 100 per cent. and increases the $I^2 R$ loss in the unfavorably situated bars adjacent to the collector rings almost 200 per cent.

It has been generally assumed that this considerable advantage of the six-phase over the three-phase machine is reduced in case of lower power-factors. It can be shown mathematically (see appendix 1) that the distribution in case of a phase displacement of 15 degrees giving a power-factor of 96.6 per cent.; that is, a wattless current equal to about 27 per cent. of the energy current, is as indicated in the lower half of Fig. 1. In this case it will be noted that the average heating of the whole winding for the same load is in the case of the six-phase operation increased from 0.27 to 0.33 of the reference figure, which is the heat developed by the same direct current load mechanically derived. In the case of the three-phase operation, the average $I^2 R$ loss rises by a lesser proportion from 0.57 to 0.65, but the addition of the wattless current has also the peculiar effect of shifting the heat distribution from one side to the other of the collector ring tap, considerably reducing the heating of the bars to one side of the tap and greatly increasing that of the bars on the other side. A lagging component shifts the heating to one side of the taps, and a leading current to the other side. It will be noted that the bar to one side of the collector ring tap is heated in the case of the six-phase operation to the extent of 0.71 of the reference figure, or about twice the average and three and a half times the minimum, whereas the corresponding bar of the three-phase machine is heated to the extent of 1.75 times the reference figure, or three times the average and seven times the minimum, and two and a half times the maximum with the same machine worked six-phase. While the distribution of the heating between slots is not as bad as that between conductors in the three-phase case, since conductors adjacent to the taps lie in the same slots with others midway between taps, a considerable difference of temperature will exist between the two conductors in one slot in case of a heavy overload at low power-factor. It will be shown later that practically all overloads on compound-wound machines are at a low power-factor. Lower power-factors increase this heating and further crowd it into a few bars.

Even if the maximum heating were the same for the two methods of operation, the addition of three collector rings might be warranted by the better distribution of six-phase operation, but with the maximum heat generation two and a half times as great (even with a good power-factor) with only three collector rings the argument is that much stronger.

Of course, a three-phase converter for a given output may by increasing its size be built with more armature copper than a six-phase converter of the same rating; but in any event the three-phase machine may be safely increased in rating some 40 or 50 per cent. with no increased losses, and with a correspondingly higher efficiency by the addition of three more collector rings and, if necessary, a corresponding extension of the commutator. This results in a corresponding reduction of core-loss per kilowatt capacity, which is a great aid to efficiency in railway work of low load-factor.

The arguments against the six-phase form of converter are three in number: first, the increased number of parts of the machine; secondly, the additional number of cables; thirdly, the alleged relative complication of the transformer circuits.

Unless extreme care is taken in the construction of a converter, to get the magnetic reluctance of all poles exactly the same, it is found that the commutation of any three-phase machine is improved by the addition of equalizing rings over and above those constituting the three collector rings. Six or more equalizing rings being advisable for this reason, the increased complication of the machine for six-phase operation is reduced to the addition of three collector rings, the necessary brush rigging and terminals. These additions are negligible in the case of large machines where each of three rings must be considerably broader than each of six in order to carry double the current, and where also the use of six rings allows the brush rigging to be divided into two equal parts, one each side of the shaft, where with three-phase converters two-thirds of the brush rigging must be on one side of the shaft. Further, the six narrow rings are better ventilated than three broad ones, and run cooler.

In the matter of cables, the objection to six-phase machines applies only to small units where the whole current of one of the three phases can be carried in one cable. In machines of 500 kw. or more, even at railway voltage, it is convenient to use six alternating current cables, two in parallel on each phase, for the supply of a three-phase converter, and in larger machines it is necessary to do so. The six-phase machine has an alternating current input per ring practically equal to one-half the direct current output, so that wherever two cables or a multiple of two are used for one pole of the direct-current output, cables of the same size may be used for the alternating-current leads, the machine being as convenient in this respect as the three-phase converter.

In the matter of transformer connections, the so-called diametrical connection is almost invariably used, each transformer having one secondary winding, the ends of which are connected respectively to two collector rings, the connection being even simpler than that of three-phase converters, in that no " Y " or delta need be made. If reactive-coils or other devices are serially connected in the low-tension alternating-current circuits, these need be, and commonly are, only three phase; one phase being connected in series with each diameter of the converter, and so to speak, boosting or lowering the voltage of both ends of the diameter. (Fig. 2). This is a positive advantage for the six-phase equipment, in that the winding of the serially connected devices need carry only one-half of the current of the winding of a similar device for a three-phase converter.

For the above reasons all converters of 500 kw. capacity and

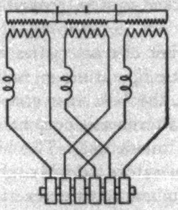

FIG. 2—Six-phase diametrical connection with three-phase reactance. Rings shown in order of connection to armature winding

over, made by one manufacturing company in this country are built for six-phase operation.

*The alternating-current starting of synchronous converters.* Some 50 per cent. of the above mentioned total of railway converters in service in this country, are equipped with switches and connections for starting the machines from rest by means of the direct application of alternating electromotive forces to their armature windings through the collector rings, these electromotive forces being a fraction of those subsequently switched on for operation. In spite of the extensive use and general success of this method of starting, advocates and users of other methods attribute great disadvantages to it. Following is a more complete statement of the case than has heretofore been set forth.

A line of 25-cycle converters with pole-arcs equal to 75 or 80 per cent. of the pole-pitch, with air-gaps of one-quarter to three-eighths of an inch, and with full load armature ampere-turns per pole approximately equal to the shunt field ampere-turns per pole (at rated voltage normal speed unity power-factor no load) and with short-circuiting squirrel-cage, anti-hunting winding embedded in the pole faces, will in general start from rest with some 20 to 25 per cent. of rated alternating voltage impressed across their collector-rings, and will take at this voltage at rest approximately twice full load current; that is, 40 to 50 per cent. of full-load volt-amperes, this current having a low power-factor, as the machine is acting under this condition as an induction motor with a variable and rather wide air-gap, the pole-face windings serving as a short-circuited secondary. When started in this way such a machine will run up to synchronism without increase of voltage, and may be locked in step by excitation of the field windings.

The air-gaps and other characteristics above mentioned, are those most desirable for operation in railway work, and have been chosen as giving the best conversion and commutation. The good qualities in alternating current starting which result from them are merely incidental. The high armature reaction relatively to that of generators is highly advisable in compound-wound converters. High armature reaction, resulting in field distortion in generators, which is disastrous to commutation, has no such effect in synchronous converters since the field distortion of the direct-current output is always balanced by the field distortion of the alternating-current input. Increase of armature reaction causes a reduction of the lagging or leading currents set up by a given percentage difference of the field strength from the proper value for unity power-factor. Machines of these characteristics will stand a most surprising departure from proper field excitation when the increased heating pointed out above is considered. This feature is advisable for machines left in the charge of suburban railway station agents or other unskilled engineers in out-of-the-way sub-stations. In extreme cases, machines of these characteristics will operate on the usual low load-factor of interurban service with no shunt-field excitation whatever, as has been proved in several cases by mistakes in connecting up the field windings, mistakes not discovered until after a considerable period of operation. Other things, including full-load efficiency, being the same, a machine of high armature reaction will have a lower core-loss than a machine of low armature reaction, and will show a higher all-day efficiency on a low load-factor such as that of railway work.

Advocates of converters with a lower armature reaction assert that machines with high armature reaction have low synchronizing power, whatever that term may mean. It is certain that machines with the characteristics above outlined, will follow without falling out of step the most violent fluctuations of speed that prime-movers can set up. One such 600-volt converter has been run with full-current output down to 50 volts. They will carry, when operating single-phase, a railway load of the usual fluctuating character of interurban service, without signs of distress. In the rough and ready service that railway converters often have to stand, it is certain that a machine with stiff fields and low armature reaction will kick out its automatic alternating current switch and go out of service more readily in case of an outside disturbance, such as a single-phase short-circuit on the alternating current lines, than will a machine with higher armature reaction. The machines outlined above do not drop out of step with direct current short-circuits when protected by the usual breakers, and the writer has never heard of a well authenticated case of one of these machines slipping a pole and continuing to run with direct-current polarity reversed, either from a direct current or an alternating current short-circuit, although this action has in one or two cases been suspected. In the matter of hunting, opinion is divided between the advisability of high or low armature reaction, but there are converters aggregating several tens of thousands of kw. capacity in service with high armature reaction even without the usual short-circuiting pole face windings.

It is interesting to compare the above minimum limit of alternating self-starting current with the minimum limit of current required for a starting induction motor before passing to the more practical field of service conditions. The torque required to start a converter from rest after a few days' shutdown may be expressed as 12 to 15 per cent. of full-load torque, the latter term representing the torque which would be set up by full-load current generated. In other words, when started as a direct-current motor, 12 to 15 per cent, of full-load current may be required, if the field strength is normal. The induction motor designed to start a six-pole converter must have four poles in order to bring the machine up to synchronism. Since an induction motor requires at least as great a current to develop a given torque at standstill as at full speed, the development of the above torque corresponds to 20 to 25 per cent. of converter full-load current input, or about one-half that required for self-starting from the alternating-current side. In other words, the advantage that the induction motor gains from design for one purpose only, is partly offset by its higher synchronous speed. With the same margin, the self-starting method should take in service about twice the volt-amperes of the other. In practice a large factor of safety in the form of a margin of voltage over that required must, of course, be allowed with either method, to cover low impressed voltage, extra friction, etc.

In actual service using this method, 25-cycle converters under 500 kw. in size, are usually started from mid-taps in the transformer windings, giving the converter one-half rated voltage, since it is expedient to locate a tap at the middle of the winding rather than at any other point more exactly suited to the purpose. Where reactive coils are used, these are connected in the starting circuit as shown in the accompanying diagram of connections, Fig. 3, since it is found that one-half voltage is sufficient to start such a converter through the usual 15 per cent. reactance. Early practice used a mid-tap in each of the three sides of the delta, but the change of phase when throwing from half to full voltage was found to give a greater swing, and the apparent unbalancing of the load with the connection shown was found to be negligible. The converter starting current under this condition, amounts to about one and three-quarters to twice full-load current, this being, by virtue of the compensator action of the half-voltage tap, equal to or less than full-load primary

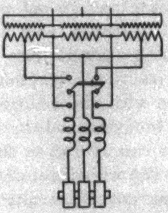

Fig. 3—Partial voltage starting connections of three-phase converter with series reactance

volt-amperes. A converter started in this way, runs up to synchronous speed in from 15 to 25 seconds with negligible sparking at the direct-current brushes.

It may lock in step with either positive or negative polarity to line, wrong polarity being customarily taken care of by a field reversing-switch, which closes the field for self-excitation without field rheostat in circuit, with a reversed connection for building up the machine when rotating in the direction set up by the alternating currents. The current sent by the armature through the field winding, acts against the flux induced by the alternating magnetizing current, driving this flux out in the form of magnetic leakage beween the poles. Friction under this condition drags the armature back until the electromotive force delivered to the brushes just reverses, when the field again reverses and holds the armature from falling back any further. The field reversing switch may then be safely thrown over into the normal connection, when the machine will build up with proper polarity to line. This action at starting voltage, calls for a volt-ampere input less than one-half full-load watts. When other compound-wound machines are carrying load in a railway sub-station, the polarity may be instantly corrected by closing the switch or switches which parallel the series field of the newly started machine with those already in operation. The division of direct current between the several series fields, serves as separate excitation to slip a pole of the newly started converter at starting voltage. With correct polarity and field excited, the machine may be thrown instantly from half voltage to full voltage with a momentary volt-ampere input not exceeding three-quarters rated watts, this input settling down to usual no-load value as soon as the field has time to build up.

Twenty-five cycle converters of 500 kw. and over, when fitted for alternating-current starting, are commonly equipped with tandem switches designed to connect them first to taps which will deliver to the windings one-third normal voltage. With this low voltage the reactive coils are cut out, the volt-amperes expended in the reactive coil during starting being thus saved. Two steps are necessary to pass from one-third to full voltage, since one jump would give too great a swing of current. These are commonly made by two double-throw switches connected tandem, to prevent the possibility of short-circuits. The arrangement is shown with complete connections for a six-phase converter with a three-phase reactance in the accompanying diagram, Fig. 4. With this arrangement, 25-cycle converters commonly take about two-thirds to three-quarters of rated full load volt-amperes in starting, and get up to speed in 20 to 25 seconds.

The advantages of this self-synchronizing method of starting in times of emergency, and at all times in small outlying substations, are obvious.

In that the same power is used for starting as for running without auxiliary apparatus other than switches, no reserve or duplicate method of starting is required, there being no more need of such a duplicate than (for example) for the starting of a steam engine. This results in simplifying the equipment and operation. When starting is accomplished by means of an induction motor, means of starting from the direct-current side are warranted by the helplessness of the converter in case the motor fails. The induction motor secondary has necessarily a high resistance in order to give good torque at standstill, and this resistance is usually made internal. As the motor is only intended to run for a short time starting cold, its design is cut fine, giving high densities. In cases of trouble giving several shutdowns in quick succession, it may become impossible to start the converters without waiting for their induction motors to cool down. Instances of this kind have occurred. Self-starting converters may be run up repeatedly as quickly as they will slow down for an indefinite period without overheating.

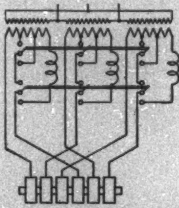

FIG. 4—One-third and two-thirds voltage starting connections of six-phase converter with diametrically connected transformers and three-phase reactance

A six-phase machine will start with two diameters and will operate with reduced capacity on two diameters, just as a three-phase machine will operate on open delta. Incidentally, this is a slight advantage of the six-phase machine over the three-phase, in that when a transformer fails, it can be readily cut out of service in the case of a six-phase machine, whereas, in two cases out of three, with a three-phase machine, it is necessary to make several cable alterations to preserve the alternating current starting features.

When starting with alternating currents directly applied, it is advisable to open the field circuits, as if these are left closed, considerably greater currents are required, and the starting torque is reduced. The shunt field circuits should be opened at several places, otherwise the induced voltage may be too high. The shunt-field reversing switch above mentioned, and field break-up switch being combined, no other means of opening the field should be provided, so that if this switch is left closed,

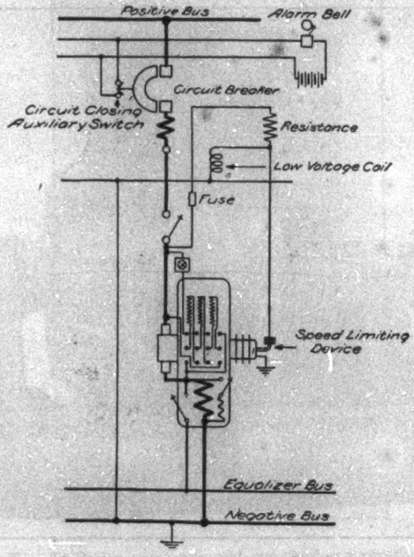
Positive Bus
Alarm Bell
Circuit Breaker
Circuit Closing
Auxiliary Switch
Resistance
Low Voltage Coil
Fuse
Speed Limiting
Device
Equalizer Bus
Negative Bus

FIG. 5—Direct-current connections of railway converter arranged for self-starting; showing four-pole, double-throw field-reversing break-up switch and series-shunt switch

the shunt field will be short-circuited through the armature, and no high voltage can result. The equalizing connections of the series field must of course, be opened during starting, and the shunt for the series field is also provided with a switch to be opened at this time to cut down the draught of current. This shunt, as customarily supplied, following the established precedent of the days of engine-driven generators, seems with its switch to be a rather useless appendage, since it is rarely, if ever, used to adjust the compounding; and it is useless for adjusting the division of load fluctuations, in that its usefulness for this purpose depends altogether on bad equalizing, which does not usually exist in compact sub-stations.

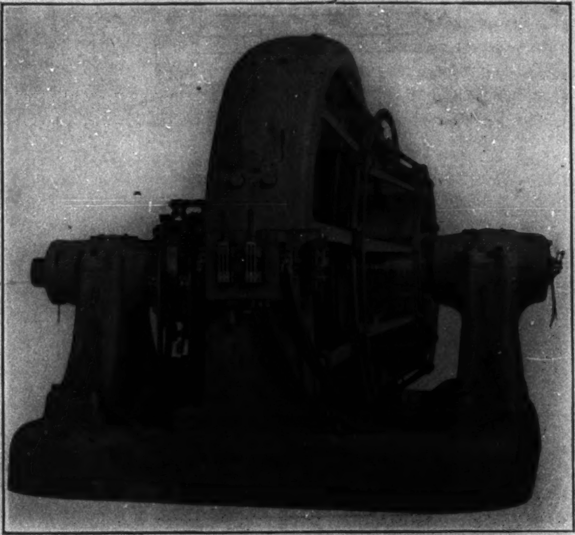

Fig. 6—1500-kw., 25-cycle, six-phase railway converter of high armature reaction, showing field-reversing, equalizer, and series-shunt switches

When a number of converters on one system are started simultaneously, as after a shutdown, the starting currents are sufficient to lower the voltage considerably, especially if but one generator is in service. The lowering of voltage at this time is, of course, immaterial, unless sufficient to prevent the converters from starting, no instance of which has ever come to the writer's knowledge It is customary on many railroads to connect up all alternating-current feeders at once after a shutdown, allowing the sub-station attendants to run up the converters as rapidly as possible. The lack of perfect synchronism between the attendants' movements and the rapid acceleration of the converters coming up to speed in a few seconds, is sufficient to avoid an overdraught of current, even in extreme cases. At other times, that is, when the system is carrying load, the starting of a converter does not cause any disturbance which it is possible to distinguish on any part of the system, from those set up by the ordinary fluctuations of railway load.

FIG. 7—Series reactance and one-third and two-thirds voltage starting switches for 1000-kw. converter

A synchronous converter is a better self-starting machine than is a constant-speed induction motor of high efficiency and the same frequency, size, and speed. Such a motor with short-circuited secondary, takes in service for starting a volt-ampere input equal to an overload of 25 to 50 per cent. Some engineers who would not hesitate to arrange for the self-starting of such an induction motor, do not favor the self-starting of the corresponding synchronous converter, so great has been the misunderstanding of this subject.

In several cities of this country converters of the largest sizes are regularly started from the alternating current side, their supply of power coming from lighting systems supplying lights through other converters from the same alternating current network. In one city, converters of 1000 and 1500 kw. capacity are supplied from a system carrying a lighting load, and although these converters are equipped with induction motors for starting purposes, the starting is usually accomplished by the above described self-starting means.

*Compounding of converters* Although it is generally known that converters cannot be compounded without reactance in the circuit, and that the smaller the reactance the greater must be the strength of the series field for the same regulation, few engineers have any idea of the best values of reactance and series field strength, or the shape of the compounding curve with different values of resistance and reactance; or, what is more important, the best transformer ratio and best setting of shunt field rheostats.

Before taking up the rather complex reactions with both resistance and reactance in circuit, a mental picture of the effect of reactance alone, in the simplest case, can be obtained from the vector diagram Fig. 8, where the large triangle represents a three-phase voltage, as delivered to a three-phase reactance and through this to a converter, the voltage of which is shown as a circle. At no load, and neglecting losses, assuming a shunt-field excitation for unity power factor; that is, no leading or lagging current, there is no drop in the reactance owing to the absence of any current, and the impressed voltage is delivered without change, the inside circle representing the converter voltage under this condition. At full load the energy current flowing through the reactance gives a reactive drop at right angles with the electromotive force delivered to the converter, which for one phase may be represented by the line $A\ B_1$. The impressed voltage of one phase may be represented by the line $O\ A$, the voltage delivered to the converter (if the converter is shunt wound) by the line $O\,B_1$, with which $A\,B_1$, the reactance drop, makes a right angle, since the current is assumed to be in phase with the converter or delivered electromotive force, and the reactance drop is normal to the current. If now the converter is compound wound, the leading current drawn by the increased field strength at full load gives a reactive drop $B_1C_1$ which increases the delivered electromotive force from the value $O\,B_1$ to $O\,C_1$, the reactive drop (which is really a rise) of the resultant current being $A\,C_1$. The middle circle drawn through the point $C_1$ and corresponding points of the other phases then represents the converter electromotive force at full load, the collector ring represented by the point $C_1$ lagging behind the impressed electro-

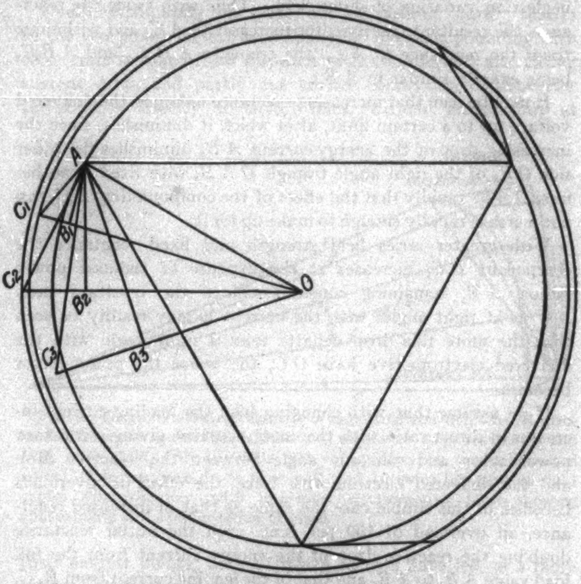

FIG. 8—Illustrating effect of reactance on voltage of compound-wound converter

motive force by the angle $A\,O\,C_1$ and being pushed out (so to speak) by the reactive drop of the leading current from $B_1$ to $C_1$.

With greater reactance, the lines $A\,B_1$ and $B_1C_1$ both become longer, always retaining the same proportion, since one is caused by the energy current and the other by the magnetizing or leading current, both of which are unaffected by the reactance in circuit, neglecting variation of shunt field. Thus with twice the reactance, the resultant reactive drop increases to $A\,C_2$ and with three times the reactance to $A\,C_3$, the triangles $A\,B_2\,C_2$ and $A\,B_3C_3$ being exactly similar to $A\,B_1C_1$.

It may be seen that increasing reactance enlarges the delivered voltage up to a certain limit, after which it diminishes, since the increasing drop of the energy current $A\,B_3$ diminishes the other side $O\,B_3$ of the right angle triangle $O\,A\,B_3$ with fixed hypothenuse $O\,A$ so rapidly that the effect of the compounding $B_3C_3$ can not increase rapidly enough to make up for it.

With greater series field strength and fixed reactance the component $B_1C_1$ increases at the expense of reduced power factor, $A\,B_1$ remaining constant. Since the resultant drop $A\,C_1$ is at right angles with the current it may readily be seen that the more this drop departs from a right angle with the delivered electromotive force $O\,C_1$ the worse the power-factor becomes.

If we assume that with changing load the leading current increases in direct ratio with the energy current giving a constant power-factor and constant angle between the reactive drop and the delivered electromotive force, the effect of overloads becomes in this simple case the same as that of increased reactance, an overload of 100 per cent. with the initial reactance doubling the reactive drop of the energy current from the full load value $A\,B_1$ to $A\,B_2$ and that of the leading current from $B_1\,C_1$ to $B_2C_2$ giving again a resultant drop of $AC_2$. In general, with any value of reactance and series field, the compounding curve is not straight, but droops on the higher loads. This can be shown by reference to the same figure, taking an extreme overload to make the drop obvious. Three times full-load current gives a reactive drop $A\,C_3$ and a delivered electromotive force $O\,C_3$ which is less than the full load or 100 per cent overload values $O\,C_1$ and $O\,C_2$ owing again to the shortening of $O\,B_3$ as $A\,B_3$ lengthens. For the same reason it will be noted that the rise of voltage from no load to full load is greater than that from full load to 100 per cent. overload. In practice, other things, such as magnetic leakage and weakening shunt field, increase the droop. It may be mentioned that $O\ A\ C_1$ represents fairly well ordinary service conditions at full load, the effect of resistance being to bring $C_1$ back to the inside circle. The saturation of reactances cuts down the overload triangles to smaller figures than here shown.

Over-compounding has gone out of fashion, partly thanks to the low power-factors accompanying over-compounding with converters supplied from a system with considerable alternating current drop, and partly due to the connection of converter sub-stations directly to trolley lines, without feeder drop at their nearest points, both of which factors have led to a more rational consideration of direct current feeder drop. It is now considered advisable to have the maximum voltage applied to the car equipments when near the sub-stations fixed, and not dependent on over-compounding caused by their own or other loads.

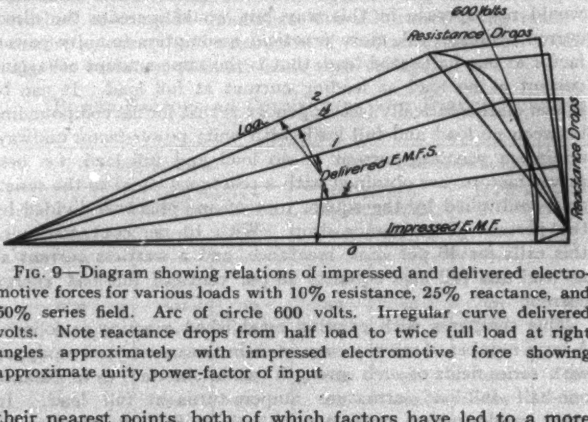

FIG. 9—Diagram showing relations of impressed and delivered electromotive forces for various loads with 10% resistance, 25% reactance, and 50% series field. Arc of circle 600 volts. Irregular curve delivered volts. Note reactance drops from half load to twice full load at right angles approximately with impressed electromotive force showing approximate unity power-factor of input

In accordance with the established custom of assuming a drop of 10 per cent. at full load, which custom has prevailed in all constant potential work since the earliest days of the incandescent lamp, converter equipments are commonly assumed to be called upon to give flat compounding at the direct-current side with a total resistance in the alternating current circuits of 10 per cent., including transformer and converter resistance, constant potential being assumed back of this 10 per cent. resistance, usually at the power house.

To reduce the average heating, compound converters should have their shunt fields so adjusted as to draw a considerable lagging current at no load. This does not materially change the compounding. For best operation under fluctuations from no load to 100 per cent. overload, the best shunt field setting would be such as to give unity power-factor at some point well above average load such as about full rated load. This would give about one-half to three-quarters full-load current lagging at no load, according to the series field strength of the converters, which is impracticable in service, as substation attendants would not operate in this way, but would increase the direct current voltage. A more practical assumption is unity power-factor at one-half rated load, that is the same amount of lagging current at no load as leading current at full load. It can be shown mathematically (see Appendix 2) that for flat compounding between no load and full load, with unity power-factor midway, minimum wattless current at no load and full load, *i.e.* best power-factors, are obtained with a reactance equal to the resistance multiplied by the square root of one plus two divided by the percentage resistance drop. With 10 per cent. resistance this calls for 46 per cent. reactance, and a wattless current at no load and full load equal to 23 per cent. of full-load energy current.

This compares with existing established practice as follows: A large number of railway converters in this country are equipped with series fields of such strength (when shunted) as to balance one-half full-load armature ampere-turns at full load. In other words, such a converter with shunt field rheostat set for unity power-factor at zero load, will (over and above energy current) draw a leading current at full load equal to one-half full-load current. In line with the above argument it will be assumed that these converters have their rheostats so set as to draw a lagging input equal to one-fourth full load current at no load, which will give unity power-factor at approximately one-half load, and a leading component equal to one-fourth full-load current at full load.

Many of these converters are equipped with 15 per cent. reactive coils; that is, reactive coils which, with full-load current, will show across the terminals of the winding in each phase

15 per cent. of the voltage of the circuit in which they are connected. Assuming about 5 per cent. reactance in the converter (high armature reaction) 3 to 3.5 per cent. in the transformers, and 1.5 to 2 per cent. in line and cables, the total reactance in circuit to the direct current brushes amounts to 25 per cent. This represents about the maximum reactance in commercial use in this country. It will also be assumed that constant potential is delivered to this circuit with a total resistance drop including that of transformers and converter to the direct current brushes of 10 per cent. at full load.

Assuming 600 volts as the no-load pressure, the compounding for both the best value of reactance and this representative case is given in the following table, the figures being calculated by the method of complex quantities, due allowance being made for magnetic leakage and saturation of reactances from test records, also for variation of shunt fields with voltage.

POWER-FACTORS AT CONVERTERS AND DIRECT CURRENT VOLTS.

| 10% resistance | | | Unity power-factor at half load | | | |
|---|---|---|---|---|---|---|
| | 46% reactance 46% series field | | 25% reactance 50% series field | | 12.5% reactance 80% series field | |
| Load | Volts | Power factor % | Volts | Power factor % | Volts | Power factor % |
| 0 | 600 | 19 | 600 | 16 | 600 | 10 |
| 0.25 | 614 | 93 | 605 | 90 | 601 | 82 |
| 0.5 | 619 | 100 | 605 | 100 | 599 | 100 |
| 0.75 | 615 | 99 | 602 | 99 | 597 | 97 |
| 1.00 | 600 | 98 | 596 | 97 | 593 | 93 |
| 1.5 | 540 | 97 | 567 | 95 | 576 | 89 |
| 2.0 | 475 | 97 | 533 | 94 | 550 | 88 |

All power-factors below one-half load represent lagging current, while those above represent leading current.

The power factors *at the converter* are also given for the various loads, these being independent of the reactance in circuit, and dependent only on the relation of the wattless and energy inputs drawn respectively by the field excitation and the load. While the power-factor *of the input* of the 46 per cent. reactance case varies with the load, that of the input to the 25 per cent. reactance and 50% series field combination is above 99% from one-half load to one-hundred per cent overload, the leading effect of the series field almost exactly balancing the lagging effect of the reactance between these limits.

The drop in pressure of the theoretical case on overloads puts

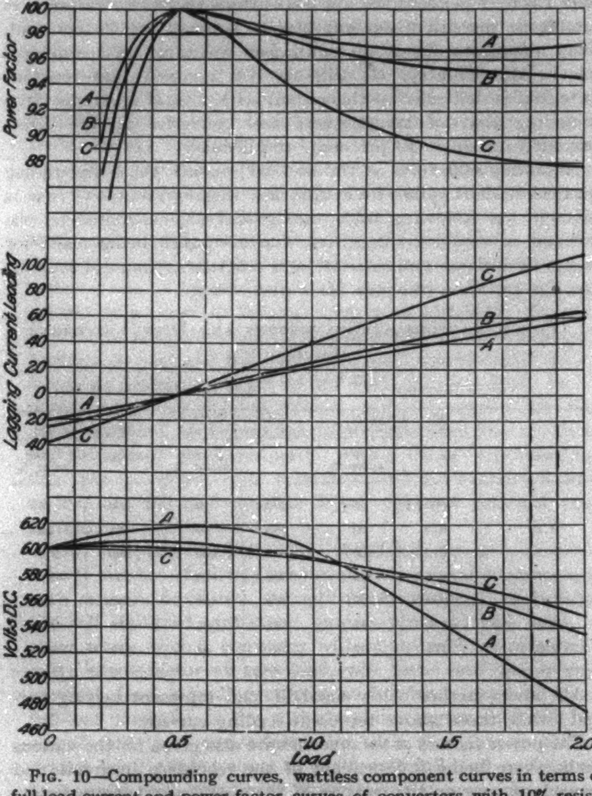

Fig. 10—Compounding curves, wattless component curves in terms of full-load current and power-factor curves of converters with 10% resistance and, A, 46% reactance, 46% series field; B, 25% reactance, 50% series field; C, 12.5% reactance, 80% series field

it out of consideration for practical service, but that of the 25 per cent. reactance case is, in the writer's opinion not objectionable, as it enables a converter to shirk its work rather than trip its breaker when overloaded, and tends in a properly designed network to throw excessive overloads to neighboring sub-stations. It also eases the blow of a short-circuit.

When separate reactive-coils are not used, dependence being placed on the internal reactance of converter, transformers and line, the total reactance of the circuit may be assumed to be as low as one-half that given above, or about 12.5 per cent., especially where converters of low armature reaction and consequently of low internal reactance are used. This represents about the minimum reactance in commercial use. To get the same regulation between no load and full load with this smaller reactance, the series field of the converter must balance an armature reaction of over 80 per cent. instead of 50 per cent; that is, a leading component equal to more than 80 per cent. of full load current must flow in the armature to balance the effect of the series field at full load. Assuming again that the shunt field is so adjusted as to give unity power-factor at half load; that is, 40 per cent. of full-load current lagging at no load, the table gives the power-factors for this case at various loads. It will be noted that while the 25 per cent. reactance gives much better regulation and only slightly lower power-factors than the best theoretical reactance, the 12.5 per cent. reactance gives much lower power-factors, the effects of which can be imagined from the heat distribution curves given in the first part of this paper.

It will be noted also that the small reactance and more powerful series field give a somewhat better regulation on heavy overloads, but it is doubtful whether this regulation can be actually reached, as it calls for heavy leading currents which it is difficult to obtain even with a machine of low armature reaction; for example, at twice full load, over full-load leading current is required. Under this condition the armature reaction is opposed to the field flux, tending to cause magnetic leakage. In this case the power-factor of the system varies with the load, as the series field greatly outweighs the influence of the reactance.

The above discussion disregards the reactance and resistance of the generators on the score that the fluctuations of load on one sub-station will not disturb the main station voltage of a large system, and will be compensated by hand adjustments of the field rheostats on a moderate size system and by automatic means on a small system, so that constant potential at the main station bus-bars may be assumed.

Records of compounding tests under similar conditions check these results as closely as might be expected, consistent results from tests under service conditions being unobtainable owing to fluctuations of other loads, voltage, etc.

Such a high reactance as the maximum above calculated might give instability, but no such case has ever been noticed with 25 per cent. reactance, even with high resistance drops and converters of high armature reaction without pole-face windings. In one case of extreme hunting due to excessive line drop, the writer inserted in circuit a reactance of 20 per cent., the result being a slight increase of the angle of oscillation of the armatures

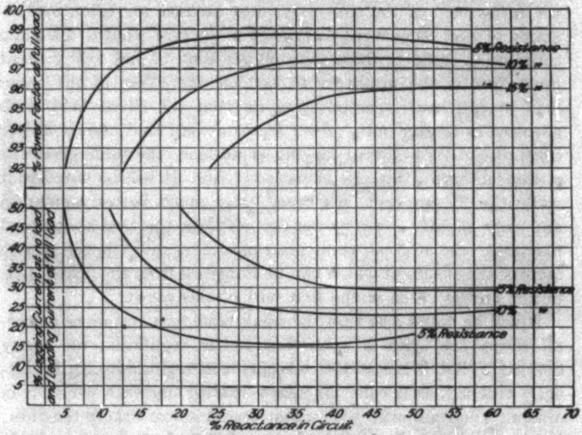

FIG. 11—Curves of wattless components and power-factors for flat compounding no load to full load with varying reactance

as noted by a stroboscopic method; but there was a great reduction of the periodicity of the oscillation, and of the effect on the voltage, due to the variable input of energy to the converters and consequent variation of line drop.

In actual practice such good results in power-factors are not obtained owing to lack of instructions concerning the setting of field rheostats. Transformers for compound converters are almost invariably designed to give a secondary voltage adapted to the ratio of conversion at no-load unity power-factor; in other words, if the ratio of conversion is 0.62, calling for 370 volts to give 600 direct voltage, the transformers are designed to give 370 volts instead of 390 volts or more, as they should do to deliver normal direct voltage with proper lagging current at no load. Even where transformers of proper ratio are in use, or the alternating voltage is sufficiently high, the tendency of human nature to push up the direct voltage tends to cut out the no-load lagging component and lower the power-factor on load.

This is particularly the case where power-factor indicators are installed in the circuits of the converters. Even where these instruments are properly connected, which frequently is not the case, the natural tendency of the attendants is to bring up the excitation on starting a converter until the power-factor indicator shows approximately unity power-factor. These instruments are frequently so connected as to show the power-factor at a point with considerable reactance between it and the converter. In this case their readings are absolutely misleading, an indicated power-factor of 97 per cent. leading (for example) often meaning a power-factor at the converter of 90 per cent. or less. While it may be possible to get attendants to set their rheostats for proper voltage, if this does not call for more than 25 per cent. of full-load current at no load, which does not make much of a showing on an alternating current ammeter capable of reading twice full load, 40 per cent. is much more difficult.

In city work with comparatively small fluctuations, converters of the above series field characteristics, have been installed, but without series reactive coils, the argument being that these are unnecessary on comparatively steady loads. It would be much more satisfactory to omit the series winding and install the reactance, in order to give the attendants an opportunity to adjust their voltage by hand with smaller wattless currents.

In general, the writer contends that best practice, with systems approximating 10 per cent. resistance, is the increase of the natural reactance of the circuits to approximately 25 per cent., and the use of a series field of such strength as to balance about one-half full-load armature ampere-turns, with transformer ratios such as to give normal direct voltage with at least one-quarter full-load current lagging at no load; converter field rheostats to be set for normal direct voltage regardless of power-factor, and main station voltage to be kept constant at such a figure as will give unity power-factor at and above such a load as gives an average of one-half load or more to the converters.

The result of existing practice is low power-factors on heavy loads, particularly with converters of low armature reaction, and more particularly in circuits of small reactance, which would probably give trouble in many cases, especially with three-phase converters, but for the low load-factors of interurban railway work and the heavy overloads for which the converters are designed.

## APPENDIX I.

If I = direct current per path in armature of converter

and $\alpha$ = angle in electrical degrees between middle of one section (between collector taps) and plane of commutation, assumed neutral

and $\phi$ = angle of lag between current and counter electromotive force, alternating current

and $\beta$ = angle between middle of section and any bar of resistance, $r$.

Then alternating current per path in winding of three-phase

machine $= I \dfrac{8 \sin (\alpha + \phi)}{3 \sqrt{3} \cos \phi}$

Resultant current $= I \left[ 1 - \dfrac{8 \sin (\alpha + \phi)}{3 \sqrt{3} \cos \phi} \right]$

Heating of bar $= I^2 r \left[ 1 - \dfrac{8 \sin (\alpha + \phi)}{3 \sqrt{3} \cos \phi} \right]^2$

Ratio of heating to that of same load mechanically generated $= \left[ 1 - \dfrac{8 \sin (\alpha + \phi)}{3 \sqrt{3} \cos \phi} \right]^2$

Average ratio $= \dfrac{1}{\pi} \displaystyle\int_{\beta}^{\pi + \beta} \left[ 1 - \dfrac{8 \sin (\alpha + \phi)}{3 \sqrt{3} \cos \phi} \right]^2 d\alpha$

$$= \frac{59}{27} - \frac{32 \cos \beta}{3 \pi \sqrt{3}} + \frac{32}{27} \tan^2 \phi + \frac{32 \tan \phi \sin \beta}{3 \pi \sqrt{3}}$$

similarly the alternating current per path in winding of six-phase machine $= \dfrac{4 \sin (\alpha + \phi)}{3 \cos \phi}$

$$\text{Average ratio} = \frac{1}{\pi}\int_{\beta}^{\pi+\beta}\left[1 - \frac{4\sin(\alpha+\phi)}{3\cos\phi}\right]d\,\alpha$$

$$= \frac{17}{9} - \frac{16}{3\pi}\cos\beta + \frac{8}{9}\tan^2\phi + \frac{16}{3\pi}\tan\phi\sin\beta$$

These two expressions are plotted in Fig. 1. $\phi$ being $O$ in the upper curves and 15° in the lower.

Average heating of whole winding of three-phase machine

$$= \frac{2\pi}{3}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}}\left[\frac{59}{27} - \frac{32\cos\beta}{3\,\pi\sqrt{3}} + \frac{32}{27}\tan^2\phi + \frac{32}{3\,\pi\sqrt{3}}\tan\phi\sin\beta\right]d\,\beta$$

$$= \frac{59}{27} - \frac{16}{\pi^2} + \frac{32}{27}\tan^2\phi$$

Similarly the loss in the six-phase winding integrated between $\beta = \frac{\pi}{6}$ and $\beta = -\frac{\pi}{6}$ gives average

$$= \frac{17}{9} - \frac{16}{\pi^2} + \frac{8}{9}\tan^2\phi$$

## APPENDIX II.

If $E$ = impressed electromotive force

and $e_0$ = delivered electromotive force at no load

and $e_1$ = delivered electromotive force at full load

and $i_0$ = lagging current at no load

and $i_1$ = energy current at full load

and $r$, $x$ and $j$ have their usual values.

Then leading current at full load $= -i_0$ since the wattless current is assumed same at zero as at full load.

At no load $E = e_0 + i_0 x + j i_0 r$

At full load $E = e_1 + i_1 r - i_0 x + j(i_0 r + i_1 x)$

Expanding these two quantities to get absolute values (when $e_0 = e_1$ since the delivered voltage is assumed to be the same at full load as at no load) gives

$$i_0 = \frac{i_1 r}{2x} + \frac{i_1^2 r^2}{4 e_0 x} + \frac{i_1^2 x}{4 e_0}$$

This expression is plotted in Fig. 11.

Differentiating this expression with respect to $x$ to obtain the value of $x$ which give the lowest value of $i_0$ gives

$$\frac{d i_0}{d x} = \frac{-i_1 r}{2 x^2} - \frac{i_1^2 r^2}{4 e_0 x^2} + \frac{i_1^2}{4 e_0} = 0$$

$$x = r \sqrt{\frac{2 e_0}{i_1 r} + 1.}$$

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## DISCUSSION ON "THE NON-SYNCHRONOUS GENERATOR IN CENTRAL STATION AND OTHER WORK," "SOME DEVELOPMENTS IN SYNCHRONOUS CONVERTERS," AND "SOME FEATURES OF RAILWAY CONVERTER DESIGN AND OPERATION." NEW YORK, FEBRUARY 14, 1908.

**C. F. Scott:** The three papers presented to-night deal with alternating-current apparatus and show the wide variations in methods which are practicable with alternating current but not with direct current.

When a new machine or method is proposed, it frequently happens that it may accomplish the specific purpose for which it is intended, but it may involve some incidental feature that renders the whole inoperative or inadmissible. Mr. Waters not only describes the induction generator but points out its various advantages over synchronous generators in construction and also its marked advantages in operation. Instead of introducing objectionable characteristics, it presents many points of advantage—reduced current on short-circuit, a smooth wave-form, and damping action due to the short-circuited element, which exerts a steadying and soothing effect throughout the whole system, that tends, in turn, to prevent hunting and surges. The paper indicates that there should be a considerable commercial field in which this type of generator will have an important application.

Mr. Stone presents six methods of voltage regulation of synchronous converters. It may be noted that the alternating-current booster may be provided with either a shunt field winding or a series field winding, or both. If a series field winding carry the current from the synchronous converter, then the compounding may be effected automatically by a practically straight-line law over a considerable range.

A comparison of the relative characteristics of the several methods of voltage regulation is of interest. In several a mechanical adjustment of the apparatus is necessary. In the case of the transformer with loops, the connection must be shifted from one loop to another. In the induction regulator mechanical rotation must take place. The reactance involves no such adjustment. In the methods in which field current is adjusted, the windings may be either shunt windings for hand control or series windings for automatic control. Auxiliary automatic control apparatus can, of course, be applied for operating rheostats, regulators, and the like. The power-factor; that is, the ratio between true and apparent watts, varies when reactance is used, or the methods in which the field poles are divided into parts which are unequally excited. The power-factor is practically unaffected when transformer loops, induction regulators, or boosters are employed. The wave-form is not affected unless it be in those cases where the field poles are divided into two or more parts. The range of voltage variation is relatively small with reactance. It is probably small with the methods in which the field poles are divided into parts, unless considerable variations in power-factor or wave-form are admissible. The range may be very large when other methods are employed. These characteristics are brought together in the following table:

| Method | Inherently automatic | Hand adjustment | Power-factor | Wave-form | Range |
|---|---|---|---|---|---|
| 1. Transformer loops....... | — | Yes | O.K. | O.K. | Large |
| 2. Reactance.............. | Yes | Yes | Variable | O.K. | Small |
| 3. Induction Regulator..... | — | Yes | O.K. | O.K. | Large |
| 4. Booster................ | Yes | Yes | O.K. | O.K. | Large |
| 5. Woodbridge............ | Yes | Yes | Variable? | Variable? | Small? |
| 6. Burnham............... | Yes | Yes | Variable? | Variable? | Small? |

**Paul M. Lincoln:** The scheme proposed by Mr. Woodbridge for changing the direct voltage of a synchronous converter, as well as the modification proposed by Mr. Burnham, is ingenious, but I believe that Mr. Stone's descriptions are altogether too brief to be satisfying to the engineer who contemplates making use of them. At the time Mr. Woodbridge's device was originally proposed, considerably over a year ago, I became familiar with an analysis of the scheme; this analysis seemed to show that the objections to the use of such a scheme outweigh the advantages. A repetition of this analysis within the last month leads to the same conclusion. Some of the steps in this analysis may be of sufficient interest to reproduce in this discussion.

*Wave-form.* The first question that arises when contemplating the use of this split-pole converter is its effect upon wave-form. These questions might naturally be put as follows: will the wave form of the split-pole converter depart materially from a sine wave? If so, how much will be the departure? Will such deformation, if it occur, have any bad effect upon the converter itself or upon any part of the system to which the converter is connected?

The first two questions are probably best answered by a series of curves which were prepared in the course of the above mentioned analysis. It is well known that with a given field form, the distributed winding of a converter gives rise to an electromotive force wave-form which is subject to quite exact determination. The division of the converter field into sections, and the provision of means to excite these sections independently of each other, gives control over the field form and therefore over the alternating-to-direct voltage ratio. As the field form changes, however, the electromotive force wave-form of the converter also changes. To what extent this takes place for certain assumed field forms is indicated in Figs. 1 to 7. Figs. 1, 2, and 3 show what may be expected of a converter with its pole divided into three sections, and Fig. 4, 5, 6, and 7 what may be expected with a pole of two parts.

Fig. 1 shows, first, six possible field forms; secondly, the electromotive force wave-forms that these field forms give rise to; and thirdly, the sine wave equivalent to the determined wave-form. The wave-forms in this series, as well as all the others, are those across an electrical diameter, in other words, they are the wave-forms that would be taken across opposite rings of a six-phase or a two-phase converter. With a field form other than a sine, the wave-form across an electrical diameter deviates from sine form less than that across any chord. It gives, therefore, the most favorable condition so far as deviation from sine form is concerned. The narrower the band of conductors the more closely will the electromotive force wave-form approach the field form. A single conductor, for instance, will give rise to an electromotive force wave-form exactly similar to the field form.

The figures at the right indicate, first, the per cent. variation in direct voltage over that which would be obtained with an electromotive force wave of sine form; secondly, the deviation in the resultant electromotive force wave from its equivalent sine wave. The sine deviations are calculated according to Institute rules.

Fig. 1 assumes a three-part pole with all three parts equal, and shows the variations through which the converter field must be carried to vary the direct voltage from +13 per cent. in the lowermost figure to —15.3 per cent. in the uppermost. The first condition entails a deviation from the equivalent sine of 74 per cent. and the second of over 23 per cent. The direct-current variation can be carried still further by further deforming the field, but at the limits given in this series the field strength at maximum direct-current variation is more than double that at minimum direct-current variation. Probably no converter designer would wish to consider a further field deformation.

Fig. 2 shows what may be expected if the outside sections of the field pole are reduced from about 33 per cent. to about to 20 per cent. each of the total pole area. The direct-current variation in this series is carried from 12.8 per cent. plus to 50.8 per cent. The first condition entails a sine deviation of about 32 per cent. and the last 50 per cent. Here again the field deformation and relative field strength are carried to an extreme at the limiting conditions.

Fig. 3 shows what may be expected if the middle section of the pole is made considerably narrower than the outside sections, a condition the reverse of that in Fig. 2. In this third series the middle section is about 20 per cent. of the total pole width. The limiting direct voltage values in this series are 8.2 per cent. plus, entailing 39 per cent. sine deviation, to 6.5 per cent. minus, entailing 12 per cent. sine deviation.

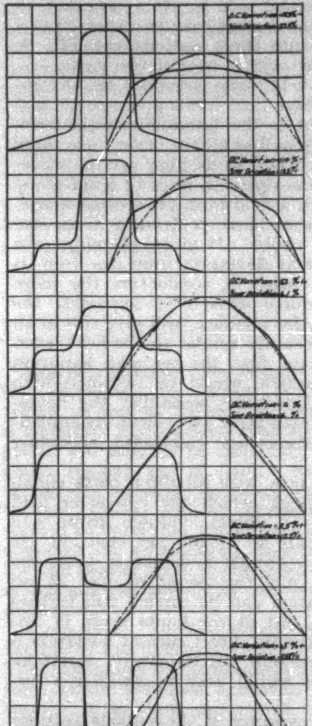

D.C. Variation = 0 %
Sine Deviation = 0 %
Series #1.

**Fig. 1**

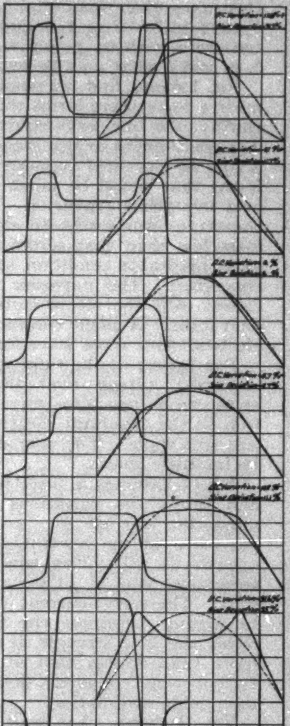

D.C. Variation = 0 %
Sine Deviation = 0 %
Series #2.

**Fig. 2**

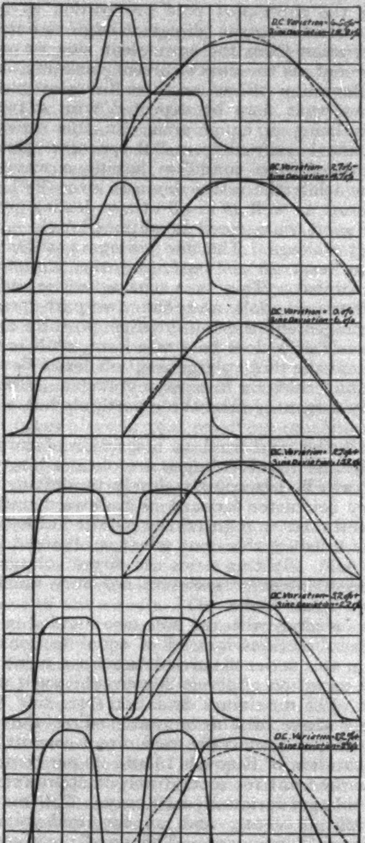

D.C. Variation – 6.5 % –
Sine Deviation – 18.9 %
D.C. Variation – 2.7 % –
Sine Deviation – 9.7 %
D.C. Variation = 0. %
Sine Deviation = 6. %
D.C. Variation = 2.7 % +
Sine Deviation = 15.2 %
D.C. Variation – 5.2 % +
Sine Deviation – 8.2 %
D.C. Variation – 8.2 % +
Sine Deviation – 8 %
Series-#3

FIG. 3

Considering the three-part pole proposition as a whole, we find that to obtain a given direct voltage variation there is entailed a deviation from the equivalent sine wave of at least as great a per cent. as the direct-current variation, and for most conditions a deviation of two or three times as great.

Fig. 4 shows what may be expected with a two-part pole, the two parts being of equal area. In this series the direct-current variation is carried from 0.2 per cent. plus, to 68 per cent. minus, the former condition having a wave-form fairly close to a sine while the latter deviates over 30%. It will be seen in this series, as well as in all others dealing with two-part poles, that a good wave-form is obtained only at the upper range of direct voltage. The mid-voltage position has a sine deviation of at least 25 per cent. and the minimum voltage is not much worse. This is a characteristic difference between the three-part pole and the two-part pole. In the three-part arrangement the mid-voltage position can be made to have a wave fairly close to a sine form, while in the two-part pole arrangement the mid-voltage position has a deviation much greater than half that for minimum voltage. However, this is about the only advantage the three-part pole has over the two-part pole.

It will readily be seen from an inspection of curves in No. 4, that the minimum direct voltages are obtained by an arrangement of field which corresponds closely to shifting the brushes of an ordinary converter forward or backward until the direct voltage between them is reduced the required amount. Instead of moving the brushes, the same effect is obtained by reversing a part of the field. In this series the direct voltage might very easily be carried down to zero with not very much additional deviation from a sine wave.

Fig. 5 shows a series with the pole face divided in 70 per cent. and 30 per cent. sections instead of equal sections. The field deformation in this series is carried to such a point as to give a direct-voltage variation of about 20 per cent. each way from the mid position. The maximum deviation from sine form occurs, as pointed out above, at the minimum direct-current position and is about 25 per cent. The mid direct-current position entails a sine deviation of between 15 and 20 per cent.

Fig. 6 is worked out for a condition of approximately 15 per cent. direct-voltage variation each way. The maximum sine deviation is 20 per cent., and at the mid-voltage position a little less than 15 per cent. The small section of field is about 20 per cent. of the total in this case.

Fig. 7 is worked out for a direct-current variation of about 10 per cent. each way and shows a maximum sine deviation of 15 per cent. and a little less than 10 per cent. at mid direct voltage. The small pole horn is about 15 per cent. of the total pole in this case.

It is probable that the proper shaping of pole pieces may be made to give deviations from sine form somewhat less than I have worked out in this series of curves, but the very nature of the case will prevent results that are materially better. They may be worse.

It is patent from the foregoing that the user of a split-pole converter can expect very considerable departures of the converter wave from the generator wave. The percentage deviation from sine form will be considerably greater than the percentage variation in direct voltage each way from mid direct-current position when considering a two-part-pole converter. For reasons that will appear later, this form is the only feasible one. The next question is: will this deviation from sine wave have any bad effect on the converter or on the system to which it is connected?

When the wave-form of a synchronous machine is at variance with that of the system upon which it is operating, currents will flow, due to these differences in the electromotive force wave. Ordinarily there are two actions taking place to limit these circulating currents; first, the impedance of the circuit through which they flow; secondly, and by far the more important, the fact that these circulating currents tend to modify the electromotive force waves of both the generating system and the receiving apparatus. If any specific piece of receiving apparatus be of relatively small capacity, as is usual, the greater part of the modification takes place in that receiving machine. In the case of split-pole converters, this field modification due to the circulating-current action is entirely absent. In order to obtain the desired direct-voltage variation, the deformation of field and consequently of wave-form must be carried to the required point. The efforts of the circulating currents to bring back the field form to normal must be neutralized and overcome by the exciting force tending to deform the field. The only impediment in the way of these circulating currents, therefore, is simply the impedance of the circuit. On a very large system the impedance outside the converter becomes reduced very close to zero and practically the only impedance offered is, therefore, that of the converter armature itself.

Commercial considerations usually call for a direct-current variation of 10 to 15 per cent. each way from normal. The analysis already given shows that with such a direct-current range a third harmonic under maximum deviation conditions of 15 per cent. is quite possible. Mr. J. E. Woodbridge has assigned 5 per cent as the value of the reactance of the armature of a converter. For third-harmonic frequency this value will become 15 per cent. Assuming such a converter to be direct connected to a very large alternating-current system, a triple-harmonic current will result, of a volume equal to the full-load current of the converter. Still higher harmonic currents will flow, and the maximum deviation of the current wave will be still greater than that represented by the full-load third harmonic.

While not at all outside the range of possibility, the above conditions will be unusual, because on a very large system the

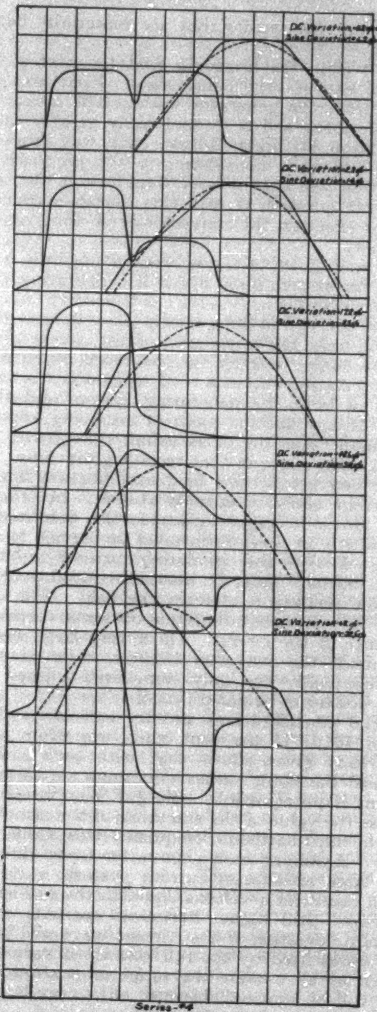
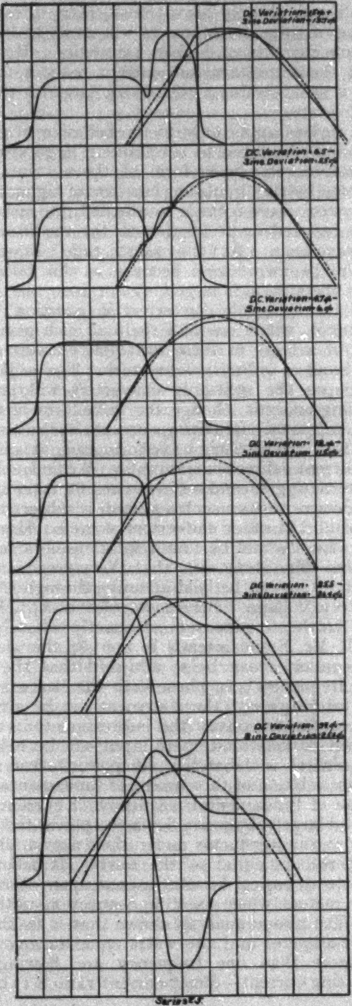

D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
Series-#4

FIG. 4



D.C. Variation
Sine Deviation
D.C. Variation 6.5 −
Sine Deviation
D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
D.C. Variation
Sine Deviation
Series E.J.

Fig. 5

converter will undoubtedly have transformers in series with it. The reactance of these transformers will assist in keeping back the circulating currents of higher harmonics. However, considering that the third-harmonic current reduces to a possible 50 per cent., it still remains a volume too large for the operating engineer to tolerate.

The above figures apply only to the behavior of one of these converters when connected to a relatively large system, where the electromotive force wave-form of the system is not perceptibly affected by the circulating currents of higher frequencies. Where the system wave-form is so affected, the circulating currents will be reduced in proportion to the modification of the generated wave-form. At the same time, however, other difficulties will be introduced, because in this latter case the wave-form of the system is largely at the mercy of the operator in charge of the split-pole converters in question. Assume a case, for instance, where one-half the load of a generating system consists of a bank of these split-pole converters, and the other half a bank of ordinary converters. The adjustments of direct voltage on the split-pole converters will, as indicated in the foregoing analysis, change the wave-form of the system. This, in turn, will cause circulating currents in the ordinary converters that will change their wave-form and, as a result, their alternating-current—direct-current ratio. We find, consequently, that the alternating-current—direct-current ratio not only of the split-pole converters on such a system is subject to modification, but also all the other converters as well. Usually such a condition of affairs would be found to be intolerable.

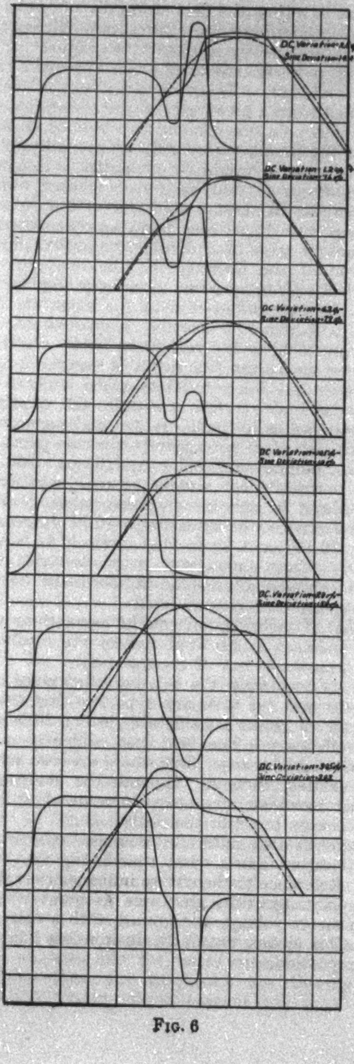
*Power-factor*. Mr. Stone says that the power-factor of these split-pole converters can be held at unity throughout the entire range of direct voltage. Before we can accept Mr. Stone's statement, a further explanation of exactly what he means is necessary. If Mr. Stone intends to convey the idea that the field of the converter can be so adujsted that the current of fundamental frequency is in phase with the electromotive force of fundamental frequency, the statement can be accepted. If, however, he means to convey the impression that the ratio of kilowatts input to kilovolt-ampere input can be held at unity, then the statement is debatable. A power-factor meter indicates the phase relation of the current of fundamental frequency to the voltage of fundamental frequency; if currents of higher frequencies and large volume are flowing, a power-factor of unity, as indicated by a power-factor meter, does not at all mean that the volt-amperes are equal to the watts. It seems probable that Mr. Stone is basing his statements upon observations of power-factor meters when used in connection with split-pole converters. The above analysis shows that it is impossible to keep the volt-amperes and the watts equal in any case where currents of more than one frequency are flowing. When a given alternating-current—direct-current ratio is to be obtained it is impossible to adjust the field strengths of one of these converters so as to eliminate these currents of higher frequencies. It is, therefore, manifestly impossible to adjust the fields so as to make unity power-factor throughout the entire range.

*Capacities and costs.* When considering the capacity that can be obtained from a given amount of material made up into one of these split-pole synchronous converters, we find that for equal outputs the amount of material for the split-pole is largely increased over what it would be ordinarily. Reference to the various series of curves that have been shown indicates that the field strengths in these converters at the maximum point vary all the way from 10 per cent. to 15 per cent. above that at the minimum point, to more than double that at the minimum point. Since the iron of the armature of the converter is capable of being worked only to a certain maximum magnetic density, it follows that the amount of iron in the armature must be increased with a split-pole converter in approximately the ratio of the minimum field to the maximum field. Reference to the series of curves shows that the ratios of minimum to maximum field in the three-part pole converters is very large, so large in fact that a converter built on this principle will require so much additional material as to make it an uncommercial machine. The same criticism does not apply to the two-part pole; in that case the ratio of minimum field to maximum field is roughly the ratio of normal direct voltage to maximum or minimum; in other words, if 10 per cent. machine range is required, the amount of material in the armature need be increased approximately only 10 per cent. over what it would be with an ordinary converter. This comparison is pointed out in order to show that a commercial machine can be made only when the two-part pole converter is considered.

The original Woodbridge scheme of using three parts makes so great an increase in size and cost of the resulting machine as to put it practically out of the question.

*Efficiency.* Considering the relative efficiencies of the split-pole converter and the ordinary type, we find that the split-pole converter increases considerably every item of loss that enters into efficiency. The field loss evidently must be considerably increased because: first, there are two parts to every pole to be excited; secondly, because the exciting tendencies of the higher harmonic frequency currents must be overcome by exciting energy put into the fields.

The iron-loss is also materially increased, particularly at the lower direct-current limits when considering the two-part-pole converter. Reference to the curves indicates that the frequency of reversals in magnetism are twice as great when obtaining a minimum direct voltage as they are with a converter of normal type. This means, naturally, an iron-loss increase in about the same proportion.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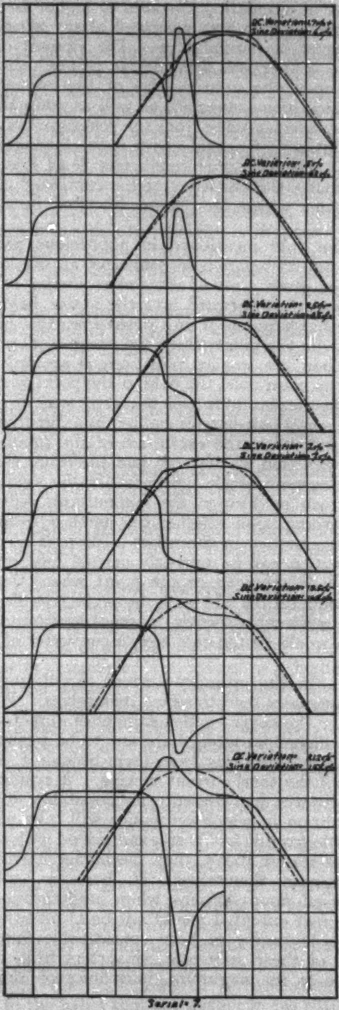
Sine Deviation=14.4%
DC Variation=1.2%
Sine Deviation=7.6%
DC Variation=4.2%
Sine Deviation=7.2%
DC Variation=14.5%
Sine Deviation=[illegible]
DC Variation=28.0%
Sine Deviation=18.8%
DC Variation=36.5%
Sine Deviation=20%

FIG. 6


D.C. Variation
Sine Deviation
D.C. Variation
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Sine Deviation
D.C. Variation
Sine Deviation
Serial 7.

FIG. 7

On account of circulating currents of higher frequencies, the armature copper-loss is also increased above what it would be with a converter of normal type. The amount of increase of this armature copper-loss depends, as pointed out in previous paragraphs, upon the relative size of the converter, and the system to which it is connected, as well as upon the amount of deviation of converter wave from the generator wave. A number of calculations of actual cases have determined that the efficiency of these split-pole converters is as low as—in most cases lower than—the efficiency of the combined converter and separate booster which Mr. Stone describes in another paragraph.

*Commutation.* As mentioned in a previous paragraph, the operation of the two-part-pole converter at the lower range of direct voltages gives a result somewhat similar to shifting the brushes backward or forward into the active field. The main difference is that a notch of any desired width can be made in the pole opposite the point where the brush rests upon the commutator. When the smaller pole-horn is excited in the same direction as the main pole, the field at the point where the brush rests upon the commutator will be very close to zero. When, however, the small pole-horn is excited in a direction the reverse of the main pole-horn, the excitation of the small horn is then in the same direction as the pole just the other side of the adjacent direct-current brush. Necessarily the field at the point where the brush rests upon the commutator will change materially, depending upon whether this small pole-horn is excited in the one direction or in the other. There is no question but that commutation can be properly carried out, even with this variation of field strength at the point where the brush rests upon the commutator. It will, however, require a machine which has considerably better inherent commutating characteristics than would be the case were a converter of the ordinary type used.

*Resonance.* In the ordinary system, circulating currents of the higher harmonics tend to efface themselves. With the split-pole converter, however, under minimum direct-voltage conditions these higher harmonics are apt to be pushed to a point where the currents resulting from them become a very considerable portion of the total current flowing. A system which contains cables always has present the possibility of there being set up a condition in which resonance will take place. In the past, very little trouble has been experienced with resonance, for the reason, as stated above, that the higher harmonics rapidly tend to eliminate themselves. If, however, split-pole converters are used upon systems where underground cables are used to any great extent, I would not be at all surprised to find the resonance becoming of very considerable importance. In changing one of these split-pole converters from its minimum direct voltage to its maximum, harmonics of almost limitless frequencies will be set up, and their amplitudes will be constantly caused to decrease and diminish. If, therefore, there is any tendency for resonance to occur anywhere in the system, the presence of one of these converters would undoubtedly search it out and supply the proper frequency of electromotive force to make it become active. Systems, therefore, which have any great amount of underground cable should carefully investigate the possibility of such a condition arising, before deciding to adopt machines of this character.

The alternative which Mr. Stone describes; namely, a converter upon which a separate machine is mounted, having the same number of poles as the converter, has, in my opinion decided advantages over this split-pole converter, for the following reasons:

1. Its wave-form remains constant and fixed, since the added voltage is of fundamental frequency, whereas the split-pole converter is apt to set up harmonics of almost any possible frequency and of amplitudes which may easily circulate currents up to full-load values.

2. The power-factor of the booster converter can be held at unity throughout its entire range of direct voltage, whereas the split-pole converter cannot.

3. The efficiency of the booster converter is not less, but in most cases considerably more than the split-pole converter.

4. The commutating conditions of the booster converter remain fixed throughout its entire range of direct voltage, whereas in the split-pole converter, careful attention must be given to the point of commutation on account of the changeableness of the field at the point where the brush rests upon the commutator.

5. The cost of the split-pole converter are greater than an equivalent capacity of simple converter, and probably as great as the combined cost of simple converter and booster.

6. The booster converter introduces no higher harmonic voltages into the system and consequently the danger of resonance is no greater than it has been in the past. The same cannot be said of the split-pole converter.

7. All parts entering into its construction are standard. It is simply an assembly of well-known and thoroughly tried out machines of standard design.

**F. G. Clark:** The paper presented by Mr. Waters advances the conclusion that certain advantages possessed by non-synchronous generators are sufficient to warrant their installation in new plants in place of synchronous generators; in present plants where new units are required; in 25-cycle gas-engine installations, and for use with synchronous converters in place of large slow-speed, direct-current generators. This proposition is sufficiently radical to call for careful consideration by any one interested in power plant work.

Speaking from the standpoint of an operating engineer, I must confess to the belief that the author in his enthusiasm over advantages, some of which must be admitted as important, neglects to consider certain disadvantages which preclude the use of the non-synchronous generator in large power stations where synchronous generators are now installed. The advantages appear to be.

1. *Excellent mechanical construction.* This probably relates to the generator, and as the stator differs but little we must pass to the rotor which is described as advantage No. 2.

2. *Absence of direct-current rotating fields.* There can be no question but that this is a distinct advantage. The only reservation is the possibility of trouble due to a small air-gap on a large machine.

3. *Absence of direct-current excitation.* As we have already discussed the rotor, this can apply only to a comparison of the exciting apparatus required in each case. The claim that the excitation of a non-synchronous generator can be controlled from a distant sub-station does not appeal to me as practical. There are a few possible happenings between a sub-station and a power station which would cause either voltage-rises or interruptions chargeable to such operation. I believe it safe to say that the synchronous converter with its starting direct-current, engine-driven generator must be located at the power station.

4. *Facility for control of load by motor control of steam governor.* The synchronous generator can be similarly controlled and no advantage obtains.

5. *Unequal distribution of load between generators does not produce cross-current.* The unequal distribution of load between synchronous turbo-generators produces a flow of magnetizing current where there is a difference in excitation, and a division of current where there is a common neutral bus-bar. There is no hunting and no undue heating, therefore no practical advantage obtains.

6. *General simplicity and flexibility of operation.* The simplicity of the rotor has been acknowledged and cannot be included here. The field rheostat and the synchronizing arrangements of the synchronous generator are not required, but a reactive coil and a governor control are requisites. No practical advantage obtains.

7. *Requires less excitation than synchronous generators.* Under certain favorable conditions on a large system the total power for excitation will be considerably less for non-synchronous generators. When, however, the difference in economy due to the compensating requirements, and the operation of very large units on very light loads is taken account of, the advantage of the non-synchronous generator will not be great, or will disappear.

8. *High efficiency.* This is not an advantage unless it be relatively to a lower efficiency in other types of generators. The author admits that there must be high speed, low fre-

quency, and low voltage or the non-synchronous will not compare favorably with the synchronous generator. This limits the comparison and eliminates the advantage of efficiency except in certain particular cases.

9. *Beneficial characteristics relatively to resonance, and short-circuits.* It is claimed that the non-synchronous generator possesses the proper characteristics to prevent, or rather lacks those characteristics of the synchronous generator which promote, high-power surges, resonance, and other electrostatic phenomena. The author assumes that resonance and other electrostatic effects are produced either by short-circuits or faulty sine waves, and that the non-synchronous generator avoids these effects by depriving short-circuits of their high power, and by giving forth only sine waves.

While admitting that these are decided advantages when compared with a majority of large installations, I do not believe that generators are ever the primary cause of electrostatic troubles outside of the station. Good line and cable construction, effective lightning protection, the grounded neutral, and automatic relays tend to lessen the primary causes and curtail the disastrous effects of insulation breakdowns. High-power short-circuits require a time-element to produce disastrous results. If the excitation of the alternator can be cut down proportionately to the speed with which the load approaches short-circuit conditions, and also if this action can be accelerated so that a short-circuit will develop in less than a second, we have accomplished just what Mr. Waters claims for the non-synchronous generator. This is accomplished at the Pennsylvania power station by using an induction motor-generator for excitation, and a Tirrill regulator for holding up the voltage. The characteristics of a combination including an induction-motor-driven exciter with series and shunt field, the latter controlled by the main generator voltage, are suitable for maintaining operation under all conditions except those due to short-circuits. When a short-circuit occurs, the field of the exciter is " boosted " in an endeavor to hold up the generator voltage. This accelerates the approach to short-circuit conditions, and produces a practically instantaneous interruption, by automatically " killing " the excitation. This scheme was adopted upon the assumption that the interruptions in railway service were of less moment than the troubles consequent upon an endeavor to hold up the excitation at all hazards. In this particular case, therefore. the non-synchronous generator does not possess an advantage.

10. *Overload capacity.* The overload capacity of five times normal full load is an advantage if we have: first, the turbine to carry this load; and, secondly, sufficient steam to drive the turbine at the higher load and higher water rate. The average synchronous turbo-generator is good for two-and-one-half to three times full load on swings. I cannot recall in my experience any case where the overload capacity of the non-synchronous

generator would have any advantage over synchronous turbo-generators.

11. *Strong balancing and damping action.* These characteristics are supposedly of benefit in parallel operation, and probably are intended for comparison with slow-speed synchronous generators. The parallel operation of synchronous turbo-alternators is sufficiently satisfactory for any advantages to be of little value. The damping action has a tendency to correct any irregularities of the sine waves of the system, thus preventing harmonics. This may or may not be an important advantage; it requires more thought for a decided opinion than I have been able to give to the subject.

12. *Adaptability to parallel operation, particularly when the prime movers are gas engines.* This is answered, so far as synchronous turbo-alternators are concerned, in the previous statement. I have never had occasion to become sufficiently familiar with gas-engine practice to venture an opinion. I hope to hear this point discussed by others.

13. *When used with synchronous converters is superior to engine-driven, direct-current generators.* This point appears to be well taken, and I believe here is the field of the non-synchronous generator. Turbine-driven direct-current generators have not proved very satisfactory, and it is doubtful if they will ever be used to any great extent. The slow-speed engine-driven sets are efficient for one point of load, and very uneconomical when the load varies through wide ranges. The non-synchronous generator and synchronous converter combination may show sufficient economy to displace engine-driven generators in some stations, and should generally be able to merit adoption when additional power is required.

The disadvantages are:

1. *Inability to furnish a lagging power-factor.* This involves the use of compensating arrangements to neutralize leading currents.

2. *Requires a lagging current for magnetization.* This involves a power-factor less than unity and may generally be considered an unimportant objection.

3. *Requires that the magnetization current be under excellent control.* This is important where there are large overhead or underground distributing systems, as the electrostatic change due to the grounding of one leg will have an immediate effect upon the power-factor.

In systems having long aerial transmission lines and rather high induction the synchronous converter would have to be considerably over-excited to produce the necessary lagging current for the generator. If an overload should occur, the supply of lagging current would increase; if the overload caused several circuits to open automatically, the induction would instantly fall to a very low value, and unless the power-factor control of the exciting converter were not equally active there would be a rise in potential in the system. This rise would be aggravated if the exciting converter were situated at a substation.

In systems having large capacity in underground cables, either artificial induction would have to be provided or the generators and turbines must be very large. It is shown that the capacity current of the Interborough system would excite a 10,000-kw., 11,000-volt, 25-cycle generator. This would not be a disadvantage if there were not periods of time when the load would be less than half this rate.

I should be pleased to learn if Mr. Waters has considered the possibilities of single-phase non-synchronous generators, particularly the 15-cycle type.

The matter of installation costs has not been gone into very deeply and would be one of the first things to be considered by a designing engineer.

Mr. Stone describes a vertical synchronous converter which appears to possess a number of improvements over the older types. The use of a step-bearing requiring oil pressure lubrication has been so thoroughly proved practical that we cannot consider it an objection. It appears to me that the greatest objection to this type of machine is the possibility of mechanical damage due to the magnetic pull of heavy armature short-circuits.

The arrangements for changing the pole relations for voltage adjustment are valuable in railway operation where the load conditions change from time to time. The device would not be so important if the generators were non-synchronous.

Mr. Woodbridge dwells at length on the following matters—six- versus three-phase converters, high versus low armature reaction, and compounding.

If the efficiency and maintenance of the two types of converters are equal, or nearly so, the operating engineer cares but little about the fine points of phase relations.

The value of compounding is generally a hard matter to decide. Mr. Woodbridge has discussed this point with commendable clearness.

High armature reaction imparts to a synchronous converter some of the characteristics of the induction motor, and enables alternating-current starting; it also means lower synchronizing power. By lower synchronizing power I mean the inability to stay in synchronism with the generator when the power-factor is low. My experience with a system where both types of converters were used, indicates that an overload condition giving a drop in voltage and sufficiently low power-factor to cause the high armature reaction converters to drop out, would have no effect on the low armature reaction converters.

I was opposed to the induction motor type of starting converters until experience proved that it was sufficient for the service requirements. I have seen a small motor start a 1,500-kw converter four times in succession without trouble, and on the Long Island Railroad system, where the interruptions have at times been rather numerous owing to lightning, there has been absolutely no trouble with the starting motors.

**Chas. P. Steinmetz:** I fully agree with Mr. Woodbridge. I should, however, consider it still better engineering not to choose the unity power-factor point at half load, but at a still higher load, somewhere between three-quarters and full load. This gives a condition of operation where the wattless lagging current at no load and light load is somewhat greater, though still moderate, but the power-factor at full load and overload is better, and the overload capacity, stability, and reliability greater.

When this type of "split-pole" converter was first brought to my attention, I was not very favorably impressed with it; I rather feared, as result of a preliminary investigation, that this machine would give considerable wave-shape distortions, a poor power-factor and poor commutation, for the same reasons that have been clearly explained by Mr. Lincoln. When the machine was built and tested I was surprised that the bad wave-shape distortion did not materialize. The machine gave a good sine wave, the power-factor was high, and the commutation good. When machine after machine, of various sizes, passed through test into commercial service without showing any wave-shape distortion, or poor power-factor, or poor commutation, I was consoled by hearing that another engineer well known to you all, had also come to the same mistaken unfavorable conclusion regarding this type of converter, and from the same point of view. There is, however, no reason why the machine should not give a perfect sine wave, unity power-factor, and good commutation.

The conclusion from this incident is, that even now it is occasionally desirable to check theoretical reasoning by experimental test, because these two do not always agree; not that the theoretical reasoning is wrong, but because in the premises on which the theoretical reasoning is based, some elements which are essential may not have been given the proper weight.

I am very much interested in the induction generator, for I once believed I had invented it. That was about fifteen years ago; but I found out afterward that long before me, the prominent French engineer, M. Leblanc, had gone over the field thoroughly, experimentally as well as mathematically, and that I was somewhat too late. Considerable work was done afterward by other investigators in developing this type of generator—Bradley, Lamme, and especially by Stanley and Kelly. It has found entrance into technical literature, and performance curves of synchronous motors or converters operated from induction generators are to be found in text-books. In the Standardization Rules of the Institute, this machine and the methods of testing it have been described for ten years. There it is given under its usual name of induction generator. I am sorry to see that Mr. Waters chooses to introduce a new name for this well-known type of apparatus, as this practice only leads to confusion. In the Standardization Rules, the name " induction generator " is analogous to the name " induction motor ", and implies the excitation of the machine by induction; the name non-synchronous machine is rather a misnomer, since the non-synchronous machine is the alternating-current commutator motor, in which the speed has no relation to the frequency. This non-synchronous machine is dependent on the speed for its frequency; it is " near synchronous ", but should no more be called a non-synchronous machine, than a direct-current shunt motor should be called an " inconstant speed motor ", because the speed varies slightly with the load. I do not think it is a good idea either, to name an apparatus by what it is *not*.

This induction generator has not been used to any great extent in engineering practice, due to the limitations imposed by its character. It cannot operate on every kind of load, but requires a load of leading current, or consumes wattless lagging current. The proper field for its use is to supply power to synchronous apparatus, motors as well as converters. I do not need to go into this, because it has been so well discussed by Mr. Waters.

The excitation of the induction generator is supplied by the wattless current delivered by the synchronous apparatus, or by the cables. There are a great many advantages in the use of an induction generator, as discussed in the paper: its greater stability and lesser liability to all those ailments incident to the flow of practically unlimited power in the system, as may occur in the synchronous machine; but it must be realized that naturally there is another side to it. If the disadvantages due to the possibility of unlimited power are eliminated, there are also eliminated the advantages resulting from an unlimited power supply. That means the voltage regulation of a system with induction generators cannot be so good as that of a synchronous generator system; for in the last analysis the voltage regulation of a system depends on the excitation of the system, on the direct-current supply to the fields. In the synchronous-generator-synchronous-converter system there are, as fixed voltage points, the generators as well as the receiving converters. In the induction-generator system the only fixed voltage points are the receiving converters, not the generators, and this cuts down the power of voltage regulation to one-half. The trouble of excessive currents is eliminated, but the regulation is somewhat impaired. The use of the wattless charging current of underground cables to help out excitation is an assistance, but at the same time is connected with some serious dangers, because the cables are of constant capacity, and the current taken by them, therefore, is proportional to the voltage. In an induction generator the voltage is proportional to the wattless current received by it, so the machine is liable to build up on its own voltage, just as a direct-current shunt generator below saturation is liable to do. That is, the more excitation is derived from constant capacity, as in underground cables, and the less from synchronous machines, the more fluctuating and unsatisfactory is the voltage regulation of the system. In developing such a system of induction generator operation, there are undoubtedly a number of features and problems which will have to be solved, and which are not always anticipated. For instance, since the voltage depends on the amount of leading current fed into the system, any connecting or disconnecting of synchronous or induction generators, changes the voltage of the system by eliminating the need for so much exciting current, and any converter change, disconnection or connection, changes the voltage of the system. The voltage regulation of the system is taken away from the generating station and located in the converter sub-stations. The latter may be, as pointed out by Mr. Waters, a rather serious feature with a generating station designed for complete voltage control. Such difficulties would be reduced where induction generators are used together with synchronous generators in the generating station.

As to the use of induction generators in a general system of distribution for light and power, probably at 60 cycles, the case stands very much less favorably for the induction generator, due to the large size of its synchronous exciters, for, after all, the synchronous machine must be considered as the exciter of the induction generator, and not the small commutating machine which excites the synchronous machine. Therefore, if the excitation is not given by the load, in using synchronous receiving apparatus, the exciter is rather a big synchronous machine. With high-speed generators of low frequency the exciting current required may be as low as 10 per cent. At lower speeds and higher frequencies it is probably nearer 30 per cent. Even if it is only 10 per cent., in addition thereto the synchronous exciting machine must also supply all the lagging currents consumed by the system of distribution. A system of distribution for light and power at 90 per cent. power-factor, is possibly above the average. 90 per cent. power factor means 44 per cent. inductance factor, and adding thereto 10 per cent. magnetizing current of the induction generator brings the total amount of exciting current up to 54 per cent.; that is, a synchronous machine used as an exciter of the induction generator would be more than half the size of it, rather a large size. This precludes the use of induction machines of the type as described by Mr. Waters for most cases of operating a general system.

In this direction, a very great advance has been made by Messrs. Stanley and Kelly, and was reported and fully discussed in a paper presented by them a few years ago before the Institute. The induction generator has two circuits, the high-frequency circuit supplying power to the outside, and the low-frequency circuit. Instead of applying the magnetizing current to the stator, as the high-frequency member, Stanley applies the magnetizing current to the low-frequency member of the induction generator; and as the volt-amperes required for excitation of the alternating field are proportional to the frequency, by exciting the induction generator, not from the high-frequency stator, but from the low-frequency rotor, Stanley cuts down the exciting volt-amperes from 50 per cent. of the generator capacity to one or two per cent. This requires, then, an alternating-current low-frequency exciter operating at one or two per cent. of the induction generator capacity, a practical machine. In this way, the great objection to the induction generator, of requiring a large synchronous exciter, can be eliminated. The exciter may be a synchronous machine or an alternating current-commutating machine—at such a low frequency as one cycle, or a fraction of a cycle per second, a commutating machine operates very satisfactorily with an alternating field—or an effective capacity as the electrolytic cell, may be used to supply the leading exciting current to the rotor. The interesting self-compounding features of this Stanley induction generator are discussed in that paper.* This method of excitation naturally also imposes certain limitations; it means that the rotor is less simple because currents have to be fed into it from outside sources; it means probably collector rings or direct connection to a generator of low frequency.

There are some very interesting features of the induction generator which have not been mentioned in Mr. Waters' paper; one is that the induction generator does not require a synchronous machine for excitation, but can also be excited by capacity, as the capacity of a cable or an electrolytic cell. The induction generator, then, assumes a characteristic very closely similar to that of the direct-current shunt generator; that is, as the amperes consumed by a constant capacity are proportional to the voltage, and the voltage of the induction generator is proportional to the amperes excitation—if the capacity is too low, the induction generator does not excite, does not energize; if the capacity is sufficiently high, it energizes and the voltage builds up until it passes beyond the bend of the saturation curve and there the machine becomes stable and is a self-exciting alternating-current generator having the same characteristics as the direct current-shunt generator. It shows indeed a very close analogy thereto. The farther beyond the bend of the saturation curve, the more stable the machine becomes. On heavy overloads, especially of lagging current, the induction generator is always liable to lose its excitation; that is, to lose its voltage, just like a direct-current shunt machine, while the synchronous machine will hold up. This may be an advantage, or it may be a disadvantage.

There is, however, one field to which I believe the induction generator is preeminently suited, and that is where water powers are operated in parallel with steam power. In those numerous cases where a water power of limited size is available, and the balance of power beyond that given by the water wheels is supplied by a steam plant, the problem is to take all the load possible from the water power and supply the only deficiency by the steam power. In this case a synchronous machine would be used on the steam engine operating at constant speed, while the induction generator connected to the water wheel would operate without governor on the water wheel—except an excess-speed cut-out. In that case the induction generator speeds up above synchronism until it consumes all the power given by the water, little or much, depending on the conditions. All the power which the water can give is thus supplied to the system; the steam engine supplies the rest. This is a case of parallel operation where a division of load is not desired, but it is desired to take all the available power from one plant, and the rest from the other. To this case the induction generator is eminently suited.

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* Alternating Current Machinery—Induction Alternators, TRANSACTIONS, A. I. E. E., 1905, Vol. XXIV, p. 851.

There is still another field, far broader than anything touched so far, in which the induction generator only can be used and the synchronous generator is out of competition—in the use of an aggregation of small water powers.

There is an enormous amount of power now going to waste; scattered in small creeks and rivers and brooks. There will come a time when the large water powers are developed and used and the problem of gathering the power of all these small streams and creeks will have to be approached and mastered. Only the induction generator can solve the problem. Consider, for instance, one of the numerous little creeks of the New England states, with a limited amount of water, a fall probably of from 200 to 2000 ft. within 5 to 20 miles. Hydraulic development on present lines there would be out of the question; to bank up the creeks, to gather considerable head, and to carry the whole pressure in a pipe-line several miles long would be so expensive as to be impracticable. But there would be a considerable amount of power, if, instead of one of these creeks, there could be combined the power of dozens or hundreds of them. While it would not be economical to develop a single small power, yet where numerous small water powers can be combined it is a practical problem which will have to be solved. The way to solve it, I think, is by building small stone dams across the creeks, just high enough to get a supply head of a few feet, to feed into a pipe of a few hundred feet long—ordinary water pipe—and thereby gather a head of some 50 or 100 ft. The water discharges from the pipe against some simple form of hydraulic turbine, and the induction generator is directly connected mechanically to the turbine, and directly connected electrically to the low-tension side of a step-up transformer. The high-tension side of the step-up transformer connects to a transmission line leading along the creek. A number of such small generating stations, which would be simple and cost but little, could be strung along the creek or river, all feeding into the same collecting line. A number of such collecting lines from different creeks could join together in a center of collection. In this manner the total power of all of these streams and creeks could be carried into one central collecting station. The power thus generated and gathered could be distributed to the consumers.

In this field the induction generator is the only feasible type of apparatus. In such a system each station must require no attention whatever beyond a systematic inspection, and must be of the simplest possible character. This excludes synchronous machines with their exciters, switchboards, turbine governors, etc. With a direct-connected low-voltage induction generator, the turbine would run without governor, absorbing whatever power is available, and speeding up until the induction generator slips above synchronism sufficiently to transfer the power to the collecting line as electric current, or, if the line should be idle, broken or so, speeding up to the free running speed, 60 to 70 per cent. above normal. Even the lubrication of the bearings may be by water. The only safety devices would be fuses to cut off the station in case of an accident, which is rather improbable with low-voltage induction machines.

**Comfort A. Adams:** Although Mr. Waters' enthusiasm has induced a somewhat optimistic point of view, there are certainly many instances where the induction generator is decidedly superior to the synchronous generator. One argument made in this connection by Mr. Steinmetz may leave a somewhat erroneous impression. He cited the case of a lagging load with a 90 per cent. power-factor, where the synchronous exciter would be obliged to supply not only the 10 per cent. exciting current for the induction generator, but also the 43.6 per cent. lagging quadrature current of the load, making necessary an exciter capacity of 53.6 per cent. This sounds like a very bad case for the induction generator; but Mr. Steinmetz failed to state that in the case of this same 90 per cent. power-factor load supplied by a synchronous alternator, the latter would be obliged to supply the 43.6 per cent. quadrature current, and that therefore the combined capacity of the induction generator and its synchronous exciter would exceed that of the synchronous alternator by only 10 per cent., the amount of the exciting current of the induction generator.

Concerning that very interesting and puzzling machine, the split-pole converter, I cannot but believe that when we know *all* the facts as to its construction and operation, the apparent gap between the results of theoretical analysis and those of experiment will be reduced to inconsiderable dimensions. Two or three factors which play some part in this explanation have already presented themselves, and will be expanded at a later date, when more information regarding the details of the machine in question is at hand.

One suggestion, however, may be made now; namely, that with a delta connection for the three-phase, or a double delta for the six-phase converter, the third and ninth harmonics disappear, which would considerably reduce the sine deviations found by Mr. Lincoln for the diametral connection.

**J. R. Bibbins:** Aside from the purely scientific interest surrounding the theory and application of the non-synchronous generator, Mr. Waters' paper is most interesting, embodying as it does the design and experience of a concrete case, which many of us have followed with interest since its installation several years ago. Personally, I am particularly interested in this type of generator from the standpoint of prime-mover design, and Mr. Waters has presented two developments which involved a number of important points. His treatment of the subject makes it reasonably clear that the flexible speed-characteristics of the non-synchronous generator, renders it particularly well adapted to direct connection to prime movers in which cyclic or angular variation of speed is permissible within unusually wide ranges, as in present synchronous generator practice. This feature would, of course, have no bearing upon turbine practice, in which angular variation is absent, but might be taken advantage of in utilizing simple forms of reciprocating engines, such as single-cyclinder steam or gas engines.

But in his remarks concerning the modern double-acting gas engine, I believe Mr. Waters' enthusiasm has led him to give an erroneous impression in regard to the possibilities of this type. To obtain the same degree of satisfaction, there does not exist such an ernomous difference between gas and steam practice, either in the matter of flywheels or dampers, as his remarks would indicate. Even if so, the matter of fly-wheels would not seem to be such a serious one, inasmuch as the cost-factor of the iron that enters into fly-wheel construction is barely 30 per cent. of the cost of the finished product in the other parts of the engine. And inasmuch as windage loss is largely occasioned by fly-wheel arms, the increase in loss due to an increased weight of rim would scarcely be noticeable, nor the increase in bearing friction due to the increased weight of rim. It seems probable, therefore, that the 3 to 5 per cent. loss due to friction and damper work ascribed to the gas-engine-driven unit would not apply to a properly designed machine of the tandem or twin-tandem type.

**Philip Torchio:** Three years ago a New York lighting company was short of 60-cycle generating capacity, and contracted with a manufacturer for the purchase of a 2000-h.p. non-synchronous generator to be coupled to a 25-cycle motor, for use as a frequency-changer. The reason of this departure was on account of the manufacturer having the frames of the machines, and the company requiring quick delivery.

On account, however, of the impracticability of making the necessary changes in the short space of time available, the proposition was dropped and I am therefore unable to give to-night the actual experience with a non-synchronous generator in connection with a large system.

I endorse what has been said regarding the use of non-synchronous machines in large power stations where the field does not seem to be very promising. I want to call special attention to the figures given by Mr. Waters, where he states that the whole system of 200 miles of high-tension feeders of the New York Edison Company, capable of supplying 150,000 kw., would only supply magnetizing current for a 2000-kw. generator, or less than two per cent. of the station generating capacity.

Regarding the point Mr. Waters makes about the non-synchronous generator reducing surges, I would qualify its practical importance. On an underground system, as of course in any system there are surges whenever the load suddenly changes, while the circuit is closed these surges are not so large as in the case when the circuit is abruptly opened. If the circuit is opened at the instant large currents are flowing, then all the energy stored in the inductance of the circuit oscillates at the period of the circuit between electrostatic energy and electromagnetic energy, and one can figure out that if there were no damping effects due to the resistance of the copper, disastrous voltages might result. As a matter of fact we do not get them, because the oil circuit-breakers open the current at zero or near zero value. I do not see how the conditions would be bettered with induction generators.

Mr. Stone says that to prevent hunting the squirrel-cage coil in the pole tips is the proper thing to use, in which I agree. However, from experience with large systems as operated in New York, it has been found that the ordinary copper grid on the pole pieces has given exactly the same results as the short-circuited coils buried in the iron of the pole tips.

I think it might be well to put on record the *whole year* efficiency of a large system operating over 100,000 kw. of synchronous converters. Including all the losses from the generating station to the low-tension bus-bars of the sub-stations; namely, the losses in transmission lines, static transformers, induction regulators, converters, and all connections—the whole-year efficiency ranges between 90 and 91 per cent. That efficiency has been obtained for several years.

**J. B. Taylor:** Mr. Clark has well expressed my ideas of Mr. Waters' paper on the induction generator. I concede to this generator two advantages: better mechanical construction, and less destructive effects on short-circuits. The other points mentioned seem to be rather in the nature of disadvantages than advantages. The matter of excitation has been already well taken up, and a point I want to dwell on is the fact that the claimed simplicity in the generating station has been obtained entirely at the expense of the sub-station. The sub-station must be ready to start up converters and excite the generators whenever necessary. Just how they would tell when it is necessary, I do not know. It would probably be a matter of establishing telephone communication, and getting the converters under way from storage-batteries, which, if available, have been installed in order to carry the load in times of emergency. These would, therefore, not be in the best condition for carrying the extra load of inverted converters. Then the generating station would have to determine, and bring the generators to, the speed of the converter. If the converters are thrown on to a lagging load, everything may speed up to a dangerous point, since lagging load, as we all know, weakens the field. In other words, there would be a great range between the low speed when connected to cables with leading currents, and high speed when connected to generators with lagging currents.

As more converters are brought to the speed of the system and connected in, more generators can also be connected in. After a time, depending on intercommunication between stations with attendant delays and misunderstandings, all will be in service.

Another point I wish to dwell on is the reference made in the papers and discussion to the disastrous effects of harmonics and departure from sine waves on operating systems. This is an old story, but at the present time I do not know of any case where the wave-form has been shown to be responsible for any case of resonance and where it has been necessary to take steps to change the wave shape or in any way to modify the constants of the system to eliminate this resonance.

There is a story that an old fiddler was playing a violin near a bridge in course of erection. Resenting some personal remarks made about his performance, he started to play, and, finding the note that resonated with some natural period of the bridge, he finally had the bridge shaking so that it would have fallen down if due apology had not been made to him. None of us ever saw such a performance, and never will, for the reason that a violin could not carry sufficient energy to supply the losses incidental to vibration of a bridge structure. Similarly, harmonics on an alternating-current system do not cause destructive resonance, mainly because there is insufficient supply of energy at the harmonic frequency to supply the accompanying losses in copper and iron. If any one knows of a case where an irregularity in the wave-shape of a system, call it the third harmonic or any other harmonic, something due to the wave shape, of the generator, has caused trouble by resonance, I shall be glad to hear of it.

**W. L. Waters:** Mr. Stone apparently advocates the use of vertical shaft converters, for a number of reasons, but taking the data on these machines as given by him, the reasons do not appear to be sufficiently important for engineers to change their standard type. Taking the 2000-kw., 250-volt converter, which he describes, the horizontal type converter operates at 115 rev. per min., while the vertical operates at 166 rev. per min. The weight given for the horizontal shaft machine is 186,000 lb. The speed has been increased about 45 per cent., while the weight has decreased about 30 per cent. Then again this increase in speed has only resulted in a reduction of about 15 per cent. in the floor space. I would point out that these reductions are obtained just as easily in a more recently designed horizontal-shaft machine. This vertical type of machine introduces new uncertainties into the design and operation, this uncertainty being specially the case in regard to the vertical footstep bearing. Roller and ball bearings have been tried for a number of years, but have never been successful for heavy work; and the alternative of an oil pressure bearing depends on maintaining a high-pressure oil circulation. The standard horizontal shaft machine with oil-ring bearings has been in service now for a number of years and there is no doubt about its operation. By the adoption of the vertical type of converter, we are merely introducing extra complication and risks and are gaining practically nothing.

Referring to Mr. Stone's remark on voltage regulation, he describes the method which makes use of a rotating armature alternating-current booster mounted on the shaft between the main armature and the collector rings, and permanently connected in series with the converter collector ring leads. In reference to this, Mr. Stone says that this development "took place abroad," and further that "a few machines of this type have been built by one of the large manufacturing companies in this country." In reference to these statements, I would like to point out that this method of voltage regulation was developed and patented by Mr. C. F. Scott fifteen years ago. and that at the present time there are 10,000 kw. of this type of converter running in New York City alone. The only reason why this method of regulation had not been adopted earlier, is that until recently it was considered preferable by operating engineers to insert induction regulators in the feeder circuits rather than to vary the converter voltage itself. The objections against this type of machine which are put forward by Mr. Stone are: the extra weight on the shaft, decreased ventilation, lesser accessibility, and increased liability to break down. The extra weight on the shaft is about 15 per cent. and can easily be taken care of. The decreased ventilation is evidently unimportant, as the temperature rise on most of these machines as actually built is about 20 degrees on full load. The question of accessibility is unimportant except in the case of repairs or cleaning out the machine.

In regard to repairs, Mr. Stone states that "any serious trouble with this smaller machine results in the dismantling of the main synchronous converter in order to repair the small booster". If Mr. Stone expects ".serious trouble" with this booster wound for 15 volts, it would be interesting to know what he expects to happen to the converter itself which is wound for twenty times this voltage. He proposes as a preferable arrangement that an overhung revolving field booster be supplied. This would mean extra collector rings and extra complication in regard to cables and increased floor space, and in addition we would have a revolving field wound for 125 and 250 volts instead of a revolving armature wound for 15 volts. Referring again to the question of floor space, I would point out that as the distance between bearing centers in a horizontal shaft converter is to a great extent decided by questions of mechanical stability, there is practically always space enough between the armature and collector rings to insert a revolving armature booster. In any case, the extra length along the shaft necessary to take care of such a booster would not exceed 10 in. or 12 in., while the extra length required for a revolving field booster would probably be 2 ft. to 2 ft. 6 in.

The question of six-phase versus three-phase is entirely a manufacturing rather than an operating engineer's question. It is to be decided by which is the cheaper machine in any individual case. The great advantage of a six-phase converter is, as Mr. Woodbridge has pointed out, that it saves armature copper. There has been a tendency on the part of some manufacturers to pay more attention to theoretical considerations than to operating conditions when deciding the amount of copper to be put on the armature of the converter. It was often decided because the total armature copper loss in the six-phase converter was only one-quarter of that of the corresponding direct-current generator, that it was advisable to reduce considerably the section of copper in order to reduce the cost. This method of designing was finally stopped by the operating engineers themselves, who refused to take converters with such small sections of copper, having found by experience that theoretical considerations were not always verified in practice. At the present time it has been shown that the only way to design converters for heavy service is to allow ample copper on the armature, and that it is advisable to design the machine irrespective of whether it is to operate three-phase or six-phase. Further, the question of using the extra three collector rings as balancing rings for the armature is again a manufacturer's question. If we want more balancing rings on a converter, they can be put on without regard to the collector rings. And in a large number of cases the extra three collector rings and cables are merely an unnecessary complication, this being especially the case in 60-cycle converters where the section of armature copper is decided by mechanical reasonss and where the current density is very low. Mr. Woodbridge', statement, "but in any event a three-phase machine may be safely increased in rating some 40 or 50 per cent. . . . . by the addition of three more collector rings" hardly needs criticism, as any engineer who has designed or operated modern converters knows that it is not the heating of the armature but the sparking or flashing at the commutator that decides the rating of a converter, and these are not influenced by change from three-phase to six-phase.

Taking the question of starting converters, the method advocated by Mr. Woodbridge which is direct application of alternating current to the armature windings through the collector rings, can only be applied satisfactorily on machines with either no dampers on the pole faces or else with only very light dampers. The reason for this being that with heavy dampers there is flashing at the commutator when starting. If we are willing to endure hunting of the converter on light loads or on certain conditions of the circuit, then we can run with light dampers and start up in this way. In any case, however, this method is not a good one from the operating engineer's point of view. Taking Mr. Woodbridge's own figures, it takes from two-thirds to three-fourths the normal rated kilovolt-amperes to start the converter in this way. The power-factor of this current will be about 20 per cent. If we have an induction motor for starting the converter, this motor will take about 30 per cent. of the full rated kilovolt-amperes of the converter when starting, and this current will have a power-factor of about 80 per cent. Thus with a starting motor we take wattless kilovolt-amperes equal to 18 per cent. of the normal rated kilovolt-amperes of the converter, while starting directly from the alternating-current side of the converter armature we take wattless kilovolt-amperes equal to 70 per cent. of the normal kilovolt-amperes; that is, starting as advocated by Mr. Woodbridge takes four times the wattless kilovolt-amperes which would be required with a starting motor. The watt kilovolt-amperes taken from the system is unimportant in either case, because it is always the wattless amperes which upset the regulation of a system. These figures show us at once, why, if a large converter system is shut down, it takes so long to get the system started again when we try to start the converters from the alternating-current side. Mr. Woodbridge states that the converters would not start up simultaneously so that the power station could carry the wattless load satisfactorily. We might add to this that in certain cases where they have tried to start up simultaneously the power station has been unable to keep the voltage high enough to start the converters.

The two most reliable methods of starting converters are:

1. An induction motor wound for slightly higher synchronous speed than the converter and with a high resistance secondary. The induction motor is thrown directly on the full alternating

voltage, and as the machines come up to speed the main alternating-current switches are closed through a resistance. This resistance limits the synchronizing current and enables the machines to get in step quietly. The resistance is then short-circuited and the induction-motor circuit is opened.

2. A small induction motor-generator starting set installed in the sub-station, this being used to start the converters from the direct-current side.

These two methods, one for starting from the alternating-current side and the other starting from the direct-current side, are undoubtedly the most reliable methods of starting a converter. The method advocated by Mr. Woodbridge requires extra complication of cables and switches, and extra taps on the transformers. It will, however, usually work out that Mr. Woodbridge's method is cheaper; and it is a question for the operating engineer to decide as to whether he prefers cheapness in first cost or reliability of operation.

I think that it is pretty evident that there must be *some* distortion of wave-form when the voltage ratio of alternating current to direct current in a converter is varied by the split-pole method; the only question is to what degree the wave-form is distorted. Mr. Steinmetz says that a sine wave is obtained under all conditions of voltage ratio. I think, however, he must be speaking in a general way, because it is evident that a pure sine wave can only be obtained when the distribution of magnetism also follows a sine wave which cannot possibly be the case under all conditions of voltage ratio in a split-pole conververter. I would point out that the power-factor as obtained on a power-factor meter would give no indication of such distortion, as a power-factor meter does not take into account the higher harmonics. Possibly Mr. Steinmetz forms his opinion from oscillograph records taken from such converters. I would like to point out that the average commercial oscillograph is, comparatively speaking, an incorrect instrument, and that its record depends to a great extent on the various adjustments of the instrument. So that unless extreme precautions are taken by an experienced and skilful operator, I would rather take the calculated wave-forms than those obtained by an oscillograph. A very simple way to show that distortion is present is to measure the power-factor of the converter running light from the direct-current side and under different conditions of voltage ratio, such power-factor being measured by taking readings of volts, amperes, and watts. I think such a power-factor reading will show at once that very considerable distortion has taken place.

Mr. Clark's criticisms are conservative and well taken, and are generally such as we would expect from experienced operating engineers when such a comparatively new proposition is put before them. He refers to the size of the air-gap on this type of machine. The clearance between the rotating and stationary part varies from ⅛ in. to ¼ in. He refers to the use of non-synchronous generators for 15-cycle single-phase traction power generation. The non-synchronous generator would be an especially good machine for such work, so long as the power-factor was not too low. Usually the power-factor in such a station can be kept about 85 per cent., and in such a case the non-synchronous generator would compare very well with a synchronous machine. It would behave considerably better than a synchronous generator on short-circuits, and would be less liable to damage, and for such a low frequency could probably be designed to be quite a little cheaper. The wattless current would, of course, in this case have to be supplied by high-speed synchronous motors running light in the power station. Mr. Steinmetz objects to the size of the synchronous motor necessary to employ in order to supply the wattless current in a system of non-synchronous generators. I would point out that each case must be considered in itself, and in the case of the gas-engine-driven station described there are 3500 kw. non-synchronous generators each requiring a 4500-kw. synchronous motor, and yet this station proves to be a commercial proposition. The size of the synchronous motor is immaterial so long as the first cost, maintenance and efficiency do not prove unfavorable.

Referring to the other non-synchronous motors mentioned by Mr. Steinmetz; namely, those of Stanley and Heyland, these were not mentioned in the paper as they were hardly considered commercial machines. The necessity for a coil winding and collector rings, on the rotating part, takes away practically all the advantage of simplicity in construction which the non-synchronous generator possesses. Such machines would hardly be considered for American power station work.

**J. E. Woodbridge:** Mr. Clark made a statement to the effect that as long as converters operate satisfactorily, a difference of a few per cent. more or less in power-factor is immaterial. This is true if the machines do operate satisfactorily, but a few per cent. difference in power-factor occasionally makes the operation quite unsatisfactory. A case has recently been reported where a converter smoked badly on a guaranteed overload. When this converter was run at unity power-factor it carried the same overload for a greater length of time with a temperature rise of only 30° cent. As I stated in my paper, railway converters work, as a rule, under such low load-factors, and are designed for such heavy overloads, that a few per cent. more or less in power-factor gives no trouble, but when converters are worked near their guaranteed loads the power-factor is relatively important.

Mr. Clark also referred to the low "synchronizing power" of converters with a high ratio of armature to field ampere-turns as compared with those of a lower ratio, and spoke of machines with the former characteristics dropping out of step on loads which the other machines would carry. My experience has been limited to railway work where machines are normally protected by circuit-breakers, and I have never heard of a case of a machine being pulled out of step by load. If the circuit-breakers are blocked, the alternating-current automatic protection, whatever it may be, unless also blocked, will operate on sufficient overload, and it is impossible to state whether this automatic protection is due to the load or to falling out of step on the part of the converters. I believe no case of this kind can be substantiated, with the exception of loads so great as to drop the voltage to zero, that is, short-circuits.

Mr. Waters gave a figure that I wish to dispute, namely, the power-factor of the starting currents of converters. With converters with narrow air-gaps, high armature reaction, low field densities, and with short-circuiting pole-face windings, I am positive that the power-factor of the starting currents is much higher than the 20 per cent, which he gave, although I have not made any direct tests on this point. For one reason, 20 per cent. would not, as a rule, give sufficient torque to start the converter in all cases, allowing for no losses or any kind whatever. A test which I do remember, showed a starting current of roughly 1500 amperes in the secondary connections which went down to 300 amperes magnetizing current when the machine reached full speed and before the field was excited. This indicates a power-factor at the converter approaching 98 per cent., but the magnetizing component was undoubtedly somewhat greater, due to the influence of the currents in the pole-face windings at lower speeds. I think that the power-factor can safely be stated to be somewhere between 70 and 80 per cent., which compares favorably with the power-factors of starting induction motors.

The input of a starting induction motor is not so greatly different from that of a self-starting converter with the characteristics described in the paper; for example, a 1500-kw. converter which I was watching this afternoon required 400-kw. for starting by means of an induction motor.

With regard to the recommendation of Dr. Steinmetz, that transformer and converter voltages should be so proportioned that compound converters would reach unity power-factor at about full load, such a radical departure from existing practice was more than I dared to suggest. Experience indicates that when transformers give such a high secondary voltage as to meet this condition, thereby giving an abnormally high direct voltage at no-load unity power-factor, either the operators run at that voltage and are glad to get it, or run at that voltage and grumble at it, either of which condition is rather unsatisfactory. With transformer ratios designed to give unity power-factor at full load, with a representative amount of resistance and reactance in circuit, unity power-factor at no load gives about 10 per cent. over voltage; that is to say, a 600-volt converter would run at no-load unity power-factor at 650 to 660 volts. To force it down to rated voltage at no load would require an alternating-current lagging input at no load amounting to 50 to 80 per cent. of the rated full-load current of the converter, according to the strength of the series field. I believe few operators would properly handle an equipment of this kind. They would simply run 5 or 10 per cent. above voltage.

**C. W. Stone:** If all the statements just made by Mr. Lincoln and apparently supported by Mr. Scott were borne out by the facts as demonstrated by the machines which have actually been built and tested, I should feel that I had made a grave mistake in coming before you and calling to your attention this new type of machine.

It is possible to calculate results which will approximate those that Mr. Lincoln has also reached. However, consideration must be given to other conditions which are apparently overlooked by Mr. Lincoln. The curves shown by Mr. Lincoln are evidently only calculated curves, and not oscillograph curves taken from actual machines. I am sorry that I did not have time to prepare some oscillograph curves which were taken across the collector rings of one of these converters, working through an extreme range in voltage. These curves approximate a sine wave. The higher harmonics mentioned by Mr. Lincoln are not apparent.

Some question was raised about the change in excitation of the main fields in order to maintain minimum current input to the converter. As a matter of fact, the main field excitation, when the load is constant, varies less than 5 per cent. for the extreme ranges in voltage; that is, from the full bucking to the full boosting voltage obtained by exciting the auxiliary field—this on a machine on which was obtained a range in voltage of approximately 175 to 350 volts, the normal being 250 volts.

Some long-continued test-runs were made on machines of various sizes, and it was found that they were all within the heating limits usually specified, and considerably below the guarantees made.

In reference to the cost of the converter built according to the Woodbridge design. In designing a 2000-kw. machine, I had a number of different designs made up to get a comparison of the cost of this type of converter with a converter using an induction regulator; I was unable to find that the converter would cost any more than a converter with an induction regulator built for the same range in direct voltage, the range in voltage being from 200 to 300 volts with normal voltage of 250 volts.

Mr. Lincoln thinks that on account of the wave distortion the converter might have a serious effect on the other apparatus operating on the system, and that in all probability the results obtained in test would not be reproduced when the machines were connected to the operating systems. In order to verify my opinion, I had the machines operated from small machines, from large machines, and in fact from all types of machines, including motor-generators, engine-driven generators, turbine-driven generators, alone and in parallel. With the same excitations the same voltages were obtained, the curves agreeing exactly, irrespective of the type of apparatus or the size of the system on which the converter was operated.

The first machine built for investigating the Woodbridge method of voltage control was made by taking a standard converter, the field spools of which were removed and replaced by some field spools made up of three sections each, on each section of which were placed the two windings in accordance with the Woodbridge scheme. The wisdom of the idea was demonstrated by the operation of this machine. The machine has been in commercial operation considerably for more than a year, and no trouble has been experienced although it has been operated under very adverse conditions.

It is true that in order to obtain the necessary space for the extra field spools, it is necessary to increase somewhat the diameter, and consequently the weight, of the whole machine; but the increase in cost of the converter due to this extra material will just about offset the cost of the induction regulator. I think I am safe in predicting that, after the idea is a little better known, and a little more experience has been had in the manufacture of these machines, there will be still further reductions in the cost.

Referring to the converters using the booster control system, I would say that I have had machines designed both with the revolving armatures and revolving fields. I have compared the cost of these machines with the cost of standard converters using induction regulators and converters made in accordance with the Woodbridge idea, and also converters made in accordance with the Burnham idea. I think that without question the converters built in accordance with the Burnham scheme will be as inexpensive as any.

The question of which type of machine, the revolving armature type of booster or the revolving field type of booster, is the better, I shall not discuss. I think that the revolving field type is the better, but this is a point upon which engineers will necessarily disagree; and in view of the new developments with the Woodbridge or Burnham type of converter, I think this whole question will be eliminated.

Mr. Waters says that roller bearing, used with the vertical type of converter is an old idea, but nobody has been able to make them work satisfactorily. I might say that the type of bearing used in this machine has been in use at Niagara Falls for several years on the Niagara Falls generators, having approximately 30 per cent. more weight and operating at 50 per cent. higher speed. No trouble whatever has been experienced with them.

**J. B. Taylor** (by letter): The proposed system using induction generators relies largely on converters for excitation, which means that these latter machines must run at power-factors other than unity. These machines as ordinarily designed are not well adapted to run at low power-factor, the increased and localized heating under these low-power factors being ably explained in Mr. Woodbridge's paper.

Too great advantages are claimed for the ease of paralleling induction generators. While exact synchronism and phase relations are not essential for paralleling induction generators, it is essential to have the speed nearly correct. For example, if the slip to give full load is one per cent., a difference in speed of two per cent. when paralleling will immediately subject the machine to twice full load, either as a motor or as a generator, and devices must be provided to indicate the proper speed. Tachometers on the machines cannot, in general, be depended on to a fraction of one per cent.; even with suitable tachometers, these are not readily seen by the switchboard attendant, who is the person most interested in knowing when speed is correct. Devices to show synchronous speed on induction motors have already been devised and placed in service, but these devices cannot be regarded as any simpler than the usual form of synchronism indicator used with synchronous generators. The proposal to connect generators to line, first, through a reactive coil, and then cut out the reactive coil, calls for additional apparatus and switches with additional complication in manipulation; means for adjusting load by pilot motors is already a well worked out device for synchronous machines.

In discussing the split-pole converter, Mr. Lincoln has shown a number of curves of calculated flux distribution and accompanying waves of electromotive force. His general objections to this type of machine on the score of power-factor, wave-shape, and efficiency have been satisfactorily answered by others who have shown that " the best proof of the pudding is in the eating thereof ", since the terrible distortions and losses anticipated have not been found in actual test. Mr. Lincoln's curves, I believe, were all based on a diametrical voltage, and do not hold for the three-phase converter or six-phase converter connected double-delta. The final effect of possible third-harmonic voltages or third-harmonic currents in the system will depend largely on combination of converter and transformer connections.

Mr. Lincoln properly points out the distinction between true power-factor and power-factor as indicated by certain types of instruments which show merely the cosine of the angle of lag rather than ratio of true watts to volt-ampere product. The case commonly referred to in bringing out this point is that of the alternating-current carbon arc, where current and voltage at the arc are in practically the same phase relation, with no angle of lag, and true power-factor is far from unity, on account of the fact that the two wave-shapes are not alike and maximum value of current does not coincide with maximum value of potential. It seems proper to point out here that the principal objection to low power-factor is the demagnetizing action on generators. For low power-factor due to wave-shapes rather than to angular displacement between current and electromotive force, the demagnetizing objection does not hold.

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# ALTERNATING-CURRENT FEEDER REGULATORS

BY W. S. MOODY

The sensitiveness of the incandescent lamp to changes in voltage, both with reference to candle-power and life of the lamp, demanded very early in the history of electric lighting a close control of the voltage on constant-potential circuits. With the small direct-current generators that were first used this was easily accomplished by the simple field adjustment of the generator, but when the size of the generators increased and several were operated in multiple, several circuits were usually operated from one station bus-bar. With the low voltage used in direct-current distribution, the feeders could not have a negligible drop; therefore an adjustable artificial loss, in the form of a rheostat, had to be inserted in each feeder and adjusted according to the load. We all remember the early direct-current stations in which these rheostats took up almost as much space as the generators, and consumed enough energy to increase materially the cost of operating the plant. In these rheostats is found the first elementary feeder regulator.

In direct-current practice, boosters, storage-batteries, and other devices have long since replaced this wasteful and unsatisfactory method of control. I refer to such historic methods of feeder control only to show how early in the art there arose the necessity of devising some means of maintaining the desired potential at the center of distribution of each feeder.

When incandescent lamps were first operated by alternating current supplied by high-voltage generators and transformers, the need of feeder regulation did not become apparent, because it was several years before generators of more than 100-kw. capacity were developed; and because attempts at multiple operation of such generators were few and generally unsuccessful. For several years then it was the practice to operate only one feeder from each generator, the desired control of potential being obtained by the field of each generator. With the development of large alternating-current generators, and with improvements in their design and the design of the governors of their prime movers that admitted of multiple operation, there developed the same necessity for the control of individual feeders, operated from high-voltage bus-bars, as had years before been experienced in direct-current distributions.

Given an approximately constant potential on the bus-bars, a feeder may be controlled: first, by a variable resistance in circuit with the feeder; secondly, by a variable reactance in series with the feeder; thirdly, by a variable capacity in multiple with the feeder; fourthly, by a transformer whose primary is in multiple with the circuit, and whose secondary is in several sections, any number of which may be thrown in series with the feeder; and fifthly, by a transformer whose primary is in multiple with the feeder, and whose secondary is in series therewith, and which is so built as to admit of shunting the magnetic flux of the primary.

The first two methods; that is, variable resistance and variable reactance, have been used to only a limited extent. The resistance is objectionable because of the loss of energy, and both forms fail in accomplishing the desired result, because they must make the inherent regulation of the feeder worse; that is, the total drop in the feeder is greater than if no such resistance or reactance were in series, and consequently every time there is a change in load, the change in voltage will be greater than if there were no such regulating resistance or reactance in circuit. While therefore with careful attention the desired voltage may, on the average, be more closely obtained by the use of such means of regulation, the variations in voltage will be increased rather than decreased.

Regulation by the use of variable capacity, obtained either from condensers or the leading current of synchronous motors, is possible only on systems having a large inherent reactance. Remarks about this method of control will be deferred until later.

Control by means of a transformer whose secondary is divided into sections, any number of which may, at the will of the operator, be placed in series with the feeder, was one of the first methods successfully worked out for the control of alternating voltage, and has proved one of the most satisfactory. Such a transformer may be readily designed to have as good regulation of its own voltage under varying load as any other transformer, and consequently its introduction into the feeder does not materially affect the inherent regulation of the system. The only engineering problem of consequence involved in the making of this form of regulator, other than the usual transformer problems, lies in the design of a switch that will allow an easy and safe cutting in and out of the various sections of the secondary.

The remaining method; namely, a transformer in which the primary flux may be shunted, ordinarily known as an induction type of regulator, can be built to have substantially as good regulation as an ordinary transformer. It does not have a detrimental effect on the inherent regulation of the system, and is particularly adapted for use on circuits carrying heavy currents, circuits that would require expensive and cumbrous switches if controlled by variation of the turns in the secondary rather than by the flux passing through the secondary.

Resistances have been used to such a limited extent that no special form has been developed, and there is nothing, therefore, to describe, even historically. Various forms of reactances, such as simple solenoids with a moving coil or core, or a moving keeper to a U-shaped core, were used to a considerable extent in some of the earlier alternating stations. As the voltage of a series reactance is so far out of phase with the voltage of a high power-factor circuit, the volt-ampere capacity of the reactance must be very large compared with the results obtained, and the inherent regulation of the system is very much interfered with by their use. Compared with their useful work their size is also greatly increased by the fact that the greatest effect is wanted when the current in the feeder is least, so that there must be turns enough to produce the maximum absorption of voltage when the minimum current is flowing. These objections to reactance control are mentioned because even engineers are sometimes surprised at the size of a reactance necessary to accomplish a given amount of control, and also because it is sometimes thought that the transformer with variable flux; that is, the induction regulator, controls by means of its reactance. This, as I shall show later on, is quite an erroneous idea.

*Transformer type of regulator.* The transformer part of this type of regulator need not differ in any essential particular from any constant potential transformer of the same size and voltage. But some attention must be given to the location of the various portions of the secondary, so that when all the secondary is in circuit, and also when only fractional portions are in circuit, these portions may be located with reference to all of the primary windings so as to have little magnetic leakage, and therefore good regulation. With moderate currents this form of regulator is the most efficient and cheapest, as its construction is that of a simple transformer and only the needed amount of secondary is in circuit at any time. The switch introduces the only complication and limitation in its use.

The difficulty of making a switch that will be durable has been well solved for a current that does not exceed 250 amperes, voltages not above 5,000 or 6,000, and the voltage per step not above 30 to 50.

It is evident that the switch must pass from one contact to the next without directly bridging the intervening space; otherwise one section of the secondary will be short-circuited and so heavy a current will flow as to cause a vicious arc when it is broken, even if the short-circuit is not on for sufficient duration to overheat the windings. When the current does not exceed 150 amperes, or the voltage between steps does not exceed 30, this short-circuit can be avoided in a very simple manner by making the moving blade just a little narrower than that necessary to bridge between contacts, and by providing any form of automatic trip that will quickly snap the blade from one contact to the next. Under these conditions the continuity of the current will be maintained through the arc that bridges the slight break, and the counter electromotive force of this arc will prevent any considerable current circulating in the section of the winding short-circuited by it.

With larger currents, or higher voltages between steps, the arc cannot be depended upon as a preventive against short-circuiting adjacent sections; the moving contact arm must be made in two parts, insulated from each other but joined through a resistance or reactance and connected to the feeder from this preventive resistance or reactance through its middle point. Such reactance or resistance suitably proportioned and connected in this manner will avoid the necessity of breaking any current at a given output of the regulator; that is, the potential generated across the reactance by the flow of the current through it can be made, with a given current, to equal the voltage between steps. Consequently when the blade leaves one of the contacts there will be no difference of potential between it and the terminal that it has left, and therefore no arc. The switch must, however, operate under all conditions of load, and therefore it is not possible to adjust for no arcing except for one definite current. With the best possible proportioning there will be arcing enough gradually to destroy contacts capable of carrying heavy currents when an attempt is made to use this form of switch for heavy duty. When it is desirable to use the switch type of voltage control for these larger currents, therefore, it becomes necessary to use separate contacts for carrying and breaking the current. One excellent way of accomplishing this is to have two electrically operated switches or contactors in series with each half of the rotating switch whose operating circuits are so connected to a small contact device on the main switch as to open the auxiliary contactor and interrupt the current to either half of the rotating switch just before it breaks contact, and again to close the circuit just after it has made contact with any of the various stationary contacts. With this arrangement all the arcing will be removed to the auxiliary contactor switches which may be made very heavy and with easily replaceable contact surfaces. Regulating switches so designed have successfully manipulated 320 amperes with 120 volts per step.

It is evident that the range of control of a feeder regulator can be doubled if the mean of the desired voltages on the feeder or feeders be maintained on the bus bar, and the regulator used both to increase and decrease this voltage. The transformer type of regulator can be made to operate in this manner by adding to the rotating switch, which enables any portion of the secondary to be thrown in circuit, an auxiliary switch that will reverse the polarity of the primary winding after the switch has been once over its range. The switch required for this reversal is not a difficult one to design, even for quite high primary voltage, since the reversal is made only when the secondary switch is on the zero point of the dial, and when, therefore, there is no current flowing in any portion of the secondary winding. Under these conditions the primary carries only magnetizing current, which, on a regulator of 50 kw. or smaller, is a current easily handled. A typical form of this type of regulator is shown in Fig. 1.

*Induction regulators.* The induction or magnetic shunt type of regulator differs from the transformer type of regulator in that all the primary and secondary windings are constantly in use. Different types vary the secondary voltage either by moving part of the iron core or one of the windings, or one of the windings and part of the core; the whole or any part of the flux generated by the primary threading the secondary according to the position of the moving part. One of the forms is interesting because of its simplicity, and because of its early development. It consisted of a U-shaped core with a primary winding around the center leg of the core, the length of the primary coil being only about one-third the

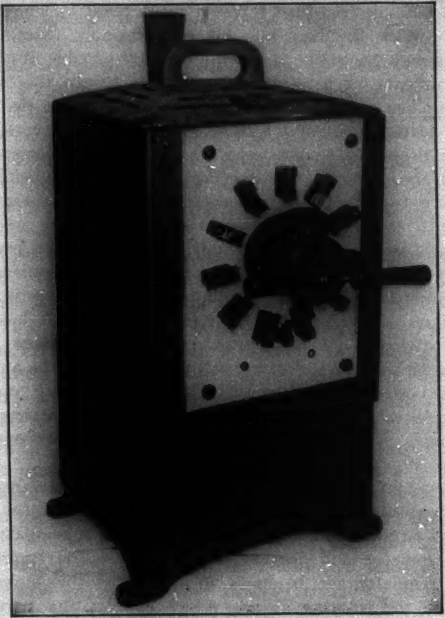

Fig. 1.—Switch type of feeder regulator with reverser.

length of the core. The wire space was long and narrow, so that the portion on the core which projected beyond the primary winding formed an air-gap of moderate reluctance even when an inch or more in width. Concentric with the primary coil was a secondary coil, having the same length of layer, to which the circuit was connected by flexible cables. By means of long screws engaging with nuts on the ends of the secondary coil, the secondary was moved along in the direction of the axis of the core from the position where it entirely covered the primary to a position at the open end of the core. When the secondary covered the primary there was little magnetic leakage, and the full secondary voltage was obtained. As the secondary was withdrawn from the primary, a larger and larger percentage of the flux crossed the air-gap rather than thread the secondary coil, until, when the secondary coil was fully withdrawn, practically all the primary flux was driven across the air-gap in the space between the primary and secondary. A reversing switch in the primary gave the secondary a double range of control. This form of regulator was developed in 1891. It is shown diagrammatically in Fig. 2. A considerable number of these are installed in that historic early transmission of power from Willamette Falls into Portland, Oregon, and are in service to-day. I mention these as being, as far as I know, the earliest successful attempt to build feeder regulators of the induction

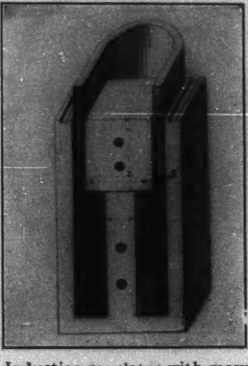

FIG. 2.—Induction regulator with movable coil.

type. This form was somewhat objectionable in that a rectilinear motion of coils or core is always more difficult to arrange for mechanically than a rotating motion; and, secondly, because the air-gap must be large to allow the secondary coils to move through it, consequently the magnetizing current tends to be greater than in other types where the air-gap may be very much less because the moving coils do not pass through the air-gap.

The second type of induction regulator developed had stationary primary and secondary coils located at right angles to each other, and a cylindrical core through which these coils passed. The center portion of the core could be rotated in such a way that any desired part of the flux of the primary coil would pass through the secondary coil.

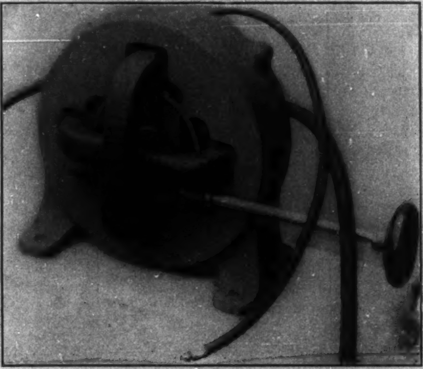

FIG. 3.—Induction regulator with movable core.

This form of regulator, see Fig. 3, is due to Dr. Steinmetz, and was really the forerunner of all the forms of induction regulators that have become so successful and useful. The air-gap in such a construction can be made very small, even less than in an induction motor, because there is no rapid rotation or wear of bearings to provide for, and consequently the magnetizing current need not be greatly in excess of that taken by a transformer with no air-gap. The particular form first developed was limited in its capacity, due to the fact that the primary and secondary were so far from each other that the mutual reactance was high, and inherent regulation consequently poor.

The third form of induction regulator to be developed historically resembles an induction motor in its general construction; the primary corresponds to the field and the secondary to the armature winding of an induction motor, not of the squirrel-cage type, but one with windings that are insulated, the terminals of which are brought out for purposes of control. This form of winding, with its many slots per pole and with only a very slight air-gap, forms a transformer having low mutual reactance between primary and secondary when the moving core and coils are in such position that the axes of the primary and secondary coils coincide. As the core is moved so that these axes are out of line, not all of the primary flux cuts the secondary winding, and the induced voltage in the secondary gradually falls, until, when each secondary coil is midway between adjacent primary coils, there is no voltage induced in the secondary. When the secondary winding is midway between the primary winding, however, it will, if it is carrying current, set up a heavy flux of self-induction which will close itself through the adjacent core between the adjacent primary coils. The result is a poor regulating device except at or near the full load position. This objection was nicely overcome by Dr. Steinmetz, who placed between each primary coil a distributed winding short-circuited on itself, so located that it is cut not by the primary flux but by the secondary self-induction flux just in proportion as the secondary moves away from the influence of the primary flux. Both the regulator with the single coil windings and that with the distributed windings can evidently be used to either raise or lower the voltage by simply rotating the moving core and coil through the angular distance corresponding to the polar pitch.

All forms of regulators so far described have been for use on single-phase circuits only. The distributed winding just described lends itself perfectly, however, to three-phase winding, and is much more efficient in three-phase than in single-phase circuit, because with the three-phase connection the short-circuited winding may be dispensed with, since the winding of the other phases naturally falls in the same location as the short-circuited winding, and acts with equal effectiveness in eliminating the flux of self-induction in the adjacent secondary.

With a multiphase winding, a secondary coil in one phase, as it passes out of influence of a given primary coil, passes into the field of a primary coil in the next phase. The result is a constant voltage generated in each of the secondary coils regardless of their position with reference to the primaries. The phase relation between this secondary voltage and the phase of the feeder circuit, with which it is in series, however, varies directly as the secondary coil is displaced with reference to the primary coils of the same phase. The result is that while the voltage measured across the secondary remains constant, its effect on the circuit, due to the phase displacement, varies from zero to maximum, and exactly as if the voltage and not the phase relation varied.

Feeder regulators of the induction type have for several years been built in all sizes from 3 kw. to 1000 kw. The larger sizes are seldom used for what could be properly called feeder regulation although some having several hundred kilowatt capacity have been built for the control of high-voltage feeder lines delivering current to sub-stations of several thousand kilowatt capacity. Most of the larger capacity, however, especially those having three-phase windings, are used to control the voltage delivered to synchronous converters, so that the voltage on the direct-current side may vary in accordance with the requirements for bus-bar potential, or for the charging of the storage-batteries used for feeder control and storage purposes.

It is rather interesting to note, in view of the fact that induction regulators larger than 300 or 400 kw. are still quite infrequently called for, that the first induction regulator which was attempted, was built fifteen years ago, and had 450 kw. single-phase capacity.

*Automatic control of feeder regulators.* A feeder regulator may have ample capacity to compensate for any changes in bus-bar potential or any varying drop in the feeder, and yet the voltage at centers of distributions may be far from satisfactory in its steadiness, due to the inattention of the station attendant or to his inability to change the regulator as rapidly as the variations in bus-bar voltage or feeder losses may require. Moreover, if an attempt is made to overcome this weakness by additional attendants, the increase in operating expenses occasioned thereby may be very considerable.

Many plants now receive current from large power systems, a large part of whose output is absorbed by railway and other motors, whose demands for current vary so rapidly that even if an attendant were constantly watching the voltmeter, in the attempt to adjust the feeder regulator to compensate for the changes in bus-bar potential, he would find it entirely impossible to control the voltage as rapidly as is necessary for good life or good service with incandescent lamps.

It was not, therefore, until about two years ago, when the first successful devices were developed for automatically operating various forms of feeder regulators, that feeder regulators assumed their proper and important sphere in electrical distribution of power.

It will be recalled that various more or less successful attempts have been made in the past to control automatically the potential of generators. The first really successful of these was perhaps the Edison regulator for direct-current generators. The device consisted simply of a rheostat with a special form of rotating arm and contact device moving through a range of only 45 degrees or so, and controlled by solenoids in shunt with the commutator of the machine. It was reasonably successful in isolated plants, put did not admit of satisfactory operation on large plants where the generators had to be operated in multiple.

Various forms of mechanism for automatically controlling the field rheostats of generators have been developed and are used with moderate success, but they are all too slow in their mechanical operation, and many of them too complicated to be extensively used.

In 1891 or 1892 Elihu Thomson made the first attempt to use the only principle of automatic control of generators that has ever proved itself entirely equal to meet all requirements. He met the problem with characteristic boldness of method. Instead of working on a rheostat which must of necessity be slow in operating, he used a series-wound exciter, and brought out two taps from the field winding of this exciter so located that when these taps were joined together a sufficient number of the series turns of the field were short-circuited to give the minimum voltage required to excite the generator under no load. When this short-circuit was removed and the full winding was in circuit, them aximum voltage necessary for the excitation of the generator under its greatest designed overload would be generated. He then designed a special form of contact-making voltmeter capable of very rapid response to changes in voltage, and connected the two taps from the field of the exciter to two contacts of the voltmeter. When the voltage was too high on the generator, the voltmeter's contacts would short-circuit this portion of the exciter's field; when it was too low it would remove this short-circuit. Except at no load and full load, of course, there was no position of equilibrium for the voltmeter. It therefore vibrated rapidly, making and breaking the shunt-circuit on the exciter's field, and gave an average voltage dependent on the percentage of time that the contacts were closed or open. The device would undoubtedly have been immediately successful if it had been first tried on a moderate size of generator requiring so small an exciter that an ordinary silver or platinum contact on the voltmeter would have stood up under the constant making and breaking of the circuit. Unfortunately, however, it was tried on an 80-pole, 400-kw. slow-speed single-phase generator. This was a very large machine for those days, and 30 kw. or so were required for excitation. It was found necessary therefore in order to protect the contacts, to have an exciter for the exciter, and to operate the voltmeter on the small exciter.

With these three magnetic systems operating in succession there was just enough lag between the operation of the voltmeter and the response in the voltage of the alternating-current generator to make the operation a failure; that is, the voltage of the generator surged over a range of three or four per cent. at a frequency of six to eight cycles per minute. It was not until Mr. Tirrill took up the problem along the same lines several years later that this ideal method of controlling the voltage of a generator was successfully perfected.

The Tirrill method differs from the Thomson method only in that the vibrating contact short-circuits a resistance in series with a shunt field exciter, and that the voltmeter is provided with a special alloy of iridium for the contact points; this makes it possible to handle current and voltage quite impossible to handle with any other metal when the circuit is so rapidly made and broken. The wonderful success of the Tirrill regulator in controlling all forms and sizes of generators is doubtless well known to us all.

A slightly modified form of the Tirrill regulator has been developed and applied to the control apparatus of feeder regulators, and as a result their value and field of usefulness were immediately increased many fold.

Of all the various forms, the induction type of regulator, free as it is from all moving contacts, lends itself most readily to automatic control. A small motor is readily attached to the same mechanism that is used for hand operation. A switch capable of starting, stopping, or reversing this motor can be easily operated magnetically, and this in turn be controlled by a modified Tirrill contact-making voltmeter. Fig. 4 shows an automatically operated regulator of this type.

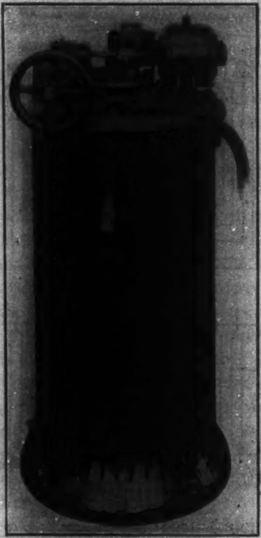

FIG. 4.—Induction regulator with distributed windings, movable core and coils, automatically operated.

When the changes of the voltage of the feeder, due either to varying load or to varying bus-bar potential, are fairly slow, this method of automatic control leaves little to be desired. When somewhat greater rapidity of control is needed, this can be accomplished by keeping the motor in constant rotation and using magnetic clutches whose excitation is controlled by the contact-making voltmeter, thereby saving the time for the motor to come up to speed.

Many feeders have such rapidly varying loads, furnishing current to elevators or hoisting machinery, for instance, or they are operated from bus-bars whose potential changes so rapidly, that some form of regulator, in which it is not necessary to move so great a mass as must be moved in the induction type regulator, becomes necessary. Under these conditions one naturally turns to the transformer type of regulator, where the only moving part is the rotating arm of the switch. But the forms of these switching devices which have been previously used offer an almost unsurmountable mechanical difficulty to rapid rotation in the step-by-step automatic snap motion that is required in passing from each step to the next.

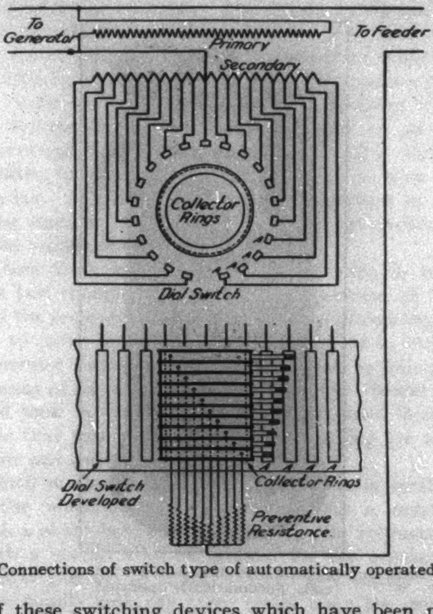
To Generator
Primary
To Feeder
Secondary
Collector Rings
Dial Switch
Dial Switch Developed
Collector Rings
Preventive Resistance

FIG. 5.—Connections of switch type of automatically operated regulator.

A new form of such switch, however, has been successfully worked out in the solving of this problem. The details of this switch will be best understood by referring to Fig. 5, but can perhaps be generally understood from the following description:

The moving element consists of a series of fingers, the majority of which are always in contact with two of the stationary contacts. Each finger is connected to a corresponding stationary collector ring by means of a suitable brush, and each collector ring is connected to the line through a preventive resistance. The individual fingers do not span the spaces between the adjacent contacts, but the arrangement of the combination is such that when the center of the top finger is on the center of one contact, the center of the bottom finger will be on the center of the next contact, the intermediate fingers being spaced so that the centers of all are on a straight line, joining the upper and lower fingers. The resistances which connect the several fingers to the line not only prevent excessive exchange currents as the fingers pass from contact to contact, but cause the change in the secondary voltage to be gradual rather than in steps. The moving member may therefore be left in any position whatever, and a much closer adjustment of voltage is obtained than by the switch which passes in one movement from each step to the next.

The moving parts of this form of switch can be made so light and compact that a very small motor, acting through suitable gearing, will move it from rest round the entire circumference of the contact points, covering the entire range of control of the regulator in from two to three seconds. Such a device, operated from a constantly revolving motor by means of the magnetic clutch and the rapidly vibrating contact-making voltmeter, cannot, of course, forestall needed changes in voltage, but it comes about as near doing so as can be imagined when parts having any appreciable mass are to be moved. Fig. 6 shows two simultaneous charts, the first showing the line potential and the second the feeder potential after having been regulated by this type of regulator. We find that with such a device, a source of varying potential which no one would think of using for any other purpose than the operation of motors, becomes available to give entirely satisfactory incandescent lighting service.

So far no attempt has been made to develop this form of regulator for handling much more than 150 amperes. The slight wear that must take place on the rapidly moving parts, and the generally increased complexity of the mechanical parts, makes it desirable to use the induction type of regulator for automatic work whenever it will fill the requirements as to speed; where it will not fill these requirements there need be no hesitancy in making use of the more sensitive rotating switch type, provided the work comes within the range of its capacity. Fig. 7 shows a regulator of this type.

Just a few words as to how the automatic regulator may be adjusted to give constant potential at the center of distribution rather than at the station. The first method that would probably occur to any one would be to bring back from the center of distribution potential wires which would be connected to the terminals of the contact-making voltmeter. This is not so simple or satisfactory as it might seem, for the expense of running the wires is by no means negligible, and unless they are carefully crossed to avoid induction, current in the feeders might

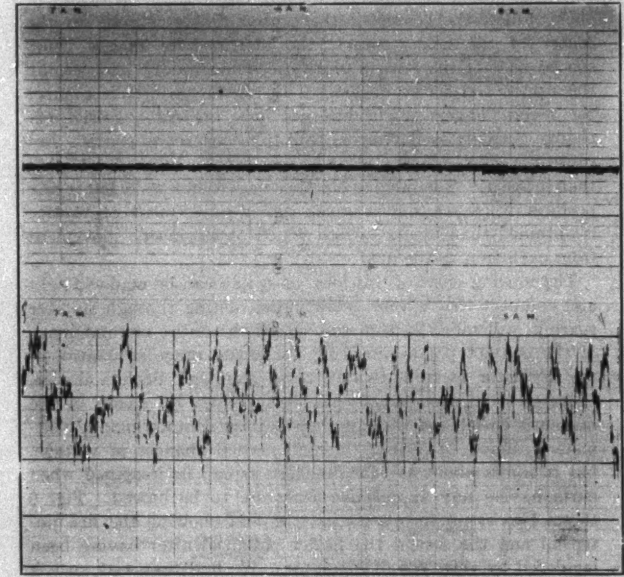

FIG. 6.—Charts showing the operation of the automatic switch type of regulator.

induce sufficient voltage to make the voltmeter's operation quite inaccurate. A simple means of accomplishing the result, which is often all that is necessary, is to have on the winding of the contact-making voltmeter an auxiliary winding connected to the secondary of a suitable current transformer, whose primary is in series with the feeder. If the windings of current transformer and voltmeter are properly proportioned and connected so that the current from the current transformer opposes the current in the shunt coil, the voltmeter will become differential in its action to any desired extent and will cause the feeder regulator to give a voltage which will increase the voltage across the feeder in proportion to the drop in the feeder. This simple method will, however, only increase the voltage in proportion to the current in the feeder. But this is not all that is necessary, as the drop in the alternating-current feeder is not only proportional to the current it is carrying, but is also roughly inversely proportional to the power-factor of this current. To

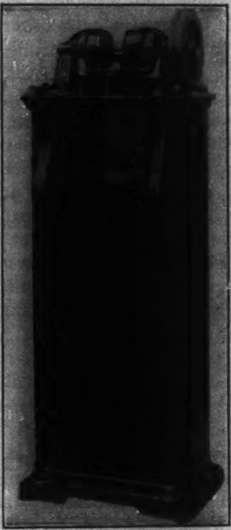

FIG. 7.—Automatically operated switch type of regulator.

obtain constant potential at the center of distribution under all conditions of load, therefore, it becomes necessary to feed the differential winding of the voltmeter from a source of voltage that will be proportional to the voltage lost in the feeder under all conditions. This is nicely accomplished by a device commonly known as a line drop compensator, which consists simply of adjustable reactance and resistance placed in series with the secondary of a current transformer placed in the feeder. By adjusting the reactance and resistance in this device so that they bear the same relation to each other as do the reactance and resistance of the feeder to be controlled, a source of voltage which will give the desired effect on the differential winding of the contact-making voltmeter will be obtained, and absolutely constant potential will be maintained at the center of distribution under all conditions of current and power-factor.

The improved quality of the service which can be given when suitable automatic potential regulators are made use of, and the increase in the life of the incandescent lamps which results therefrom, should be sufficient inducement to make the installation of automatic control well-nigh universal. There is perhaps a more direct effect accomplished by their use which would appeal more strongly to many station managers, simply because the economies resulting are more evident. I refer to decreased station attendance.

The time is fast coming when nearly all service feeders will emanate from sub-stations rather than generating stations, these sub-stations being supplied from either distant water powers or great steam generating stations. In fact, a large proportion of electrical power is so distributed already. Such stations frequently have no rotating machinery, and if they do it is usually of so simple a character that it needs very little attention. Watching the voltmeter on the various feeders, and adjusting the feeder regulators, therefore, becomes almost the sole work of the attendants in such a sub-station.

One attendant can satisfactorily watch only one voltmeter, and adjust one feeder regulator at a time, and therefore if reasonably good service under varying load or varying potential received at the sub-station is to be accomplished, it is necessary to have an attendant for almost every feeder, and even then the service may be very poor. It is in eliminating the necessity of these attendants, therefore, that the greatest direct economy can be accomplished by automatic regulators.

## DISCUSSION ON "ALTERNATING-CURRENT FEEDER REGULATORS." TORONTO SECTION, FEBRUARY 20, 1908.

**R. G. Black:** We have used regulators of all the types described and have found them to give good results in practical operation. The automatic regulator is particularly interesting inasmuch as it keeps the voltage at the centre of distribution constant and takes a great deal of work off the station operator.

I am sorry that Mr. Moody did not discuss the relative merits and disadvantages of several other types of regulators; for instance, a type consisting of a transformer, the low-tension side of which is in series with the line, and the high-tension side energized from an auto-transformer placed across the line. By means of taps brought out from the autotransformer, the voltage on the primary of the series transformer is raised or lowered and the regulation thereby effected without breaking the heavy current which is flowing in the circuit. In this way a gradual raising or lowering of the voltage may be effected, and it is the writer's opinion that there will be very much less wear at the shifting contacts. However, there may be other disadvantages which more than counterbalance this feature.

The ease with which a feeder regulator makes it possible to regulate a numbe of alternating-current circuits, from one bus-bar, stands out in great contrast with the low-tension, direct-current system, which necessitates having two or more sets of bus-bars each energized by separate generators and then switching devices to transfer the feeder from one bus-bar to another.

**J. Kynoch:** A large number of lights and some motors were required in a large building, and the only available source of supply was feeder to a suburban railway. It was found that the voltage at the end of this feeder varied from 350 to 575. It was proposed to use a direct-current motor-generator set, the motor being wound for 500 volts normal, and the generator for 220 volts. In order to keep the speed of motor and voltage of generator constant, a Tirrill regulator was arranged to be placed on the fields of each machine, the relays on the motor fields being so connected that as the voltage of the railway feeder changed, the field strength of the motor would be varied, and in this way the speed kept constant. The only other requirement was, that the design of the motor should be such that the motor should be capable of giving the required output at the minimum voltage for such length of time as such low voltage may exist.

The regulator on the generator was applied in the usual manner, and was arranged to give either constant terminal voltage at the generator or a constant voltage at the end of main lighting feeder. In this way an eminently satisfactory control of voltage was obtained from a source which under ordinary circumstances would be quite impracticable for incandescent lighting.

Another way to meet the above conditions would be to apply a Tirrill regulator to the generator fields only, and allow the motor speed to vary with changes in feeder voltage. This, of course, needs a specially designed generator to give the normal voltage at minimum speed, and also means using a field rheostat of very high resistance, in order to reduce to normal, the high voltage at maximum speed.

Mr. Moody refers to the possibility of voltage regulation by using capacity, such as the leading current from synchronous motors. I should like to enlarge upon this as follows: The voltage regulation of alternating-current power feeders having considerable reactance can be accomplished by applying a Tirrill regulator to the exciter of a synchronous motor connected to the ends of such feeder. In this way not only practically constant potential can be maintained, but also high power-factor due to the regulator varying the excitation of the synchronous motor and thus causing the same to supply leading or lagging current as the voltage of the circuit drops or increases, respectively.

This scheme is especially valuable on 60-cycle transmission lines as the inductive losses on such lines are usually considerable, and consequently the line regulation is very much worse than on a 25-cycle circuit carrying the same class of load. Of course, in order for a motor successfully to regulate a transmission line, it would be necessary for the motor to carry a reasonable proportion of the load, probably in the neighborhood of 30 per cent., but a larger proportion would be better. It is, of course, assumed that Tirrill regulators would be connected to the generators at the power station, so that the motor would not have to do an abnormal amount of regulation.

**R. S. Kelsch** (by letter): One Canadian company has a number of induction regulators in service, some of which have been in operation almost ten years. These regulators vary in size from 40 kw. to 800 kw. capacity each. There are a number of 40-kw. oil-cooled regulators used in connection with synchronous converters, and several 40 kw. air-cooled regulators used in connection with three-phase feeders. The company also has two 350-kw. air-cooled and one 800-kw. three-phase regulators used in connection with sub-station work.

In the sub-station, the power is received at a voltage which varies according to the demand made by the different sub-stations on the line. In one instance the power is received at approximately 11,000 volts stepped down to 2300 volts. This pressure is used for power service. For the lighting load, the same power is delivered to a second bus-bar through a 350-kw. regulator, which automatically maintains the voltage required, depending upon the load on the lines.

The 40-kw. regulators are used for individual feeders, where the load varies considerably. For example: the company has a feeder three miles long, which, during the day time delivers power to a large induction motor for pumping purposes. The load on this line varies during the 24 hr. from 10 to 100 per cent. and the power-factor changes from 80 to 95 per cent. It would be impossible to handle this business without induction regulators.

In one of the sub-stations, 14,000 h.p. is received, and a large portion of the power distributed locally, the balance distributed to a considerable distance. The same pressure would not suit both purposes, but the 800-kw. induction regulator makes it possible to receive a pressure suitable for local distribution, and, at the same time, transmit the balance of the power a considerable distance, delivering it at the required pressure.

During the ten years these regulators have been in service, there has not been one accident, failure to work, or interruption of any kind due to the regulator, notwithstanding the fact that most of the regulators are exposed direct to the line.

*A paper presented at the 226th Meeting of the American Institute of Electrical Engineers New York, March 13, 1908.*

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# NOTES ON ELECTRIC HAULAGE OF CANAL BOATS*

BY LEWIS B. STILLWELL AND H. ST. CLAIR PUTNAM

The following notes are based upon the results of tests conducted by the authors during the autumn months of 1907 on a section of the Lehigh Canal near Mauch Chunk, Pennsylvania. The object of the tests was to determine:

*a.* Pull required to propel canal boats at various speeds and with varying numbers of boats in tow.

*b.* The relative merits, for the purpose contemplated, of locomotives supplied by trolley and operating upon a track of 42-in. gauge, and a monorail system.

*c.* The best speed and length of tow as fixed by physical conditions.

*d.* The power required to operate the canal between Coalport and Bristol.

*e.* The equipment required for such operation.

The data presented in this paper are included under the headings "a", "b", and "c" of the foregoing summary.

The upper section of the canal from Lock No. 2 to Coalport, a distance of 10,095 ft., is equipped with the "Locomotive System". The plan and profile of this section of the canal are shown in Fig. 2. On this section an ordinary mining locomotive is used. Two locomotives were tested, each weighing under test conditions 16,000 lb. without testing instrument equipment and crew. Each locomotive is equipped with two direct-current motors of 28 h-p., operating on 500-volt trolley circuits. The locomotive wheels are 28 in. in diameter and gear-ratio of 69/15. The wheel-base is 44 in. The outline drawing of this locomotive is shown in Fig. 6.

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* By the courtesy of Mr. W. A. Lathrop, President of the Lehigh Coal & Navigation Company, for whom the tests were made, we are permitted to present to the Institute such results of our investigation as are not purely local in their significance but comprise data more or less applicable to the general problem of electric operation of canals.

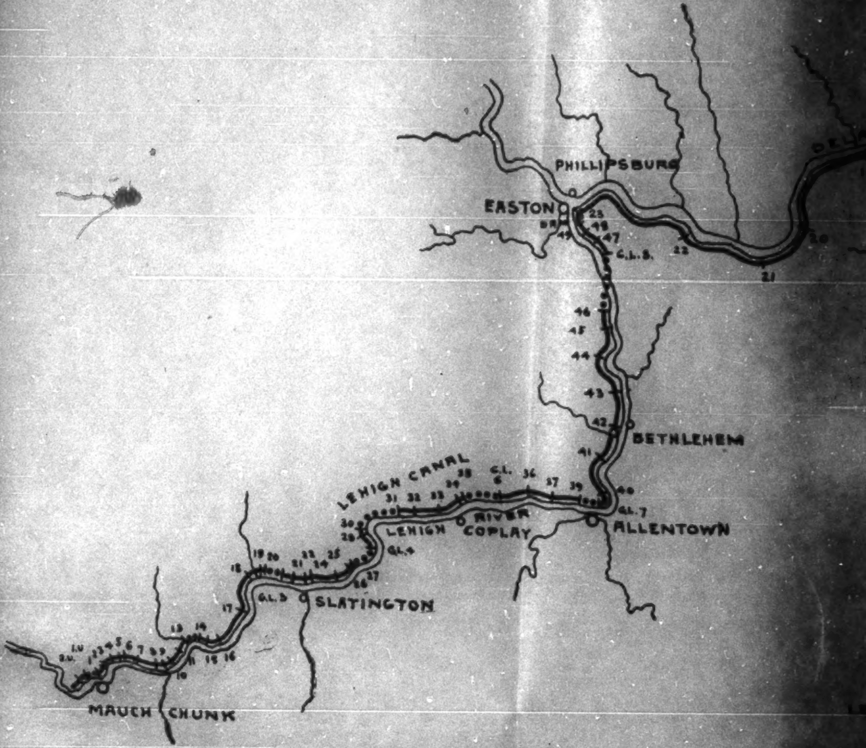
The locomotives were operated on a track of 42-in. gauge and ballasted on the river section with broken stone, elsewhere with gravel. Forty-pound rails were used. The track was uneven and comparatively rough.

On this section, two levels of the canal, aggregating 5600 ft. in length, were in the open river exposed to the river currents. The voltage of the trolley circuits was varied to obtain various towage speeds; an experimental generating plant, connected as shown in diagram No. 9, being used as a source of power supply.

The section of the canal from Lock No. 3 to Lock No. 7, a distance of 10,555 ft., was equipped with the " Monorail System " illustrated in Fig. 3. On this section three traction machines were used. These machines are hereinafter designated " Tractors." Two of these tractors (Nos. 1 and 2) were manufactured in this country. The electric equipment of each comprised one direct-current 40-h.p. motor. The gear-ratio was 5.78 to 1; diameter of wheels 12 in., and length of wheel-base 42 in. The construction is illustrated in Fig. 7. The ratio of leverage on lever wheels was 4.7 to 1; that is to say, the lower wheels are pressed upward against the lower face of the rail with a force 4.7 times the drag on the tow line. The adhesion of the machine, therefore, is a function not only of its weight but also of the pull which it exerts. Each tractor weighs 6,450 lb., and, under test conditions with instruments and crew, 7,350 lb. Tractor No. 3 was manufactured in Paris, and equipped with one 25-h.p. mining motor. Its wheels are 11.25 in. in diameter, gear-ratio is 3.4 to 1, and wheel-base 42 in. The general design is the same as that of Tractor No. 1 and is shown in Fig. 7.

Owing to the fact that the frame of this tractor had not been designed to receive a motor of the exact dimensions of that with which it was equipped, it was impossible to locate the motor in its proper position; it was necessary, therefore, to use 500 lb. counterweight to secure equilibrium of the machine. The weight of the tractor complete was 5,093 lb.; including counterweight, test apparatus, and crew, 6,493 lb.

The mechanical construction and workmanship of Tractor 3 made it superior to Tractors Nos. 1 and 2, as was evidenced


PHILLIPSBURG
EASTON
D.R.
49
23
48
47
G.L.8.
22
20
21
DEL
46
45
44
43
42
BETHLEHEM
41
LEHIGH CANAL
38
C.L.
6
36
37
39
40
GL.7
31
32
33
34
30
29
LEHIGH RIVER
COPLAY
ALLENTOWN
GL.4
19
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21
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27
26
17
GL.3
SLATINGTON
13
14
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1.U
2.U.
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MAUCH CHUNK

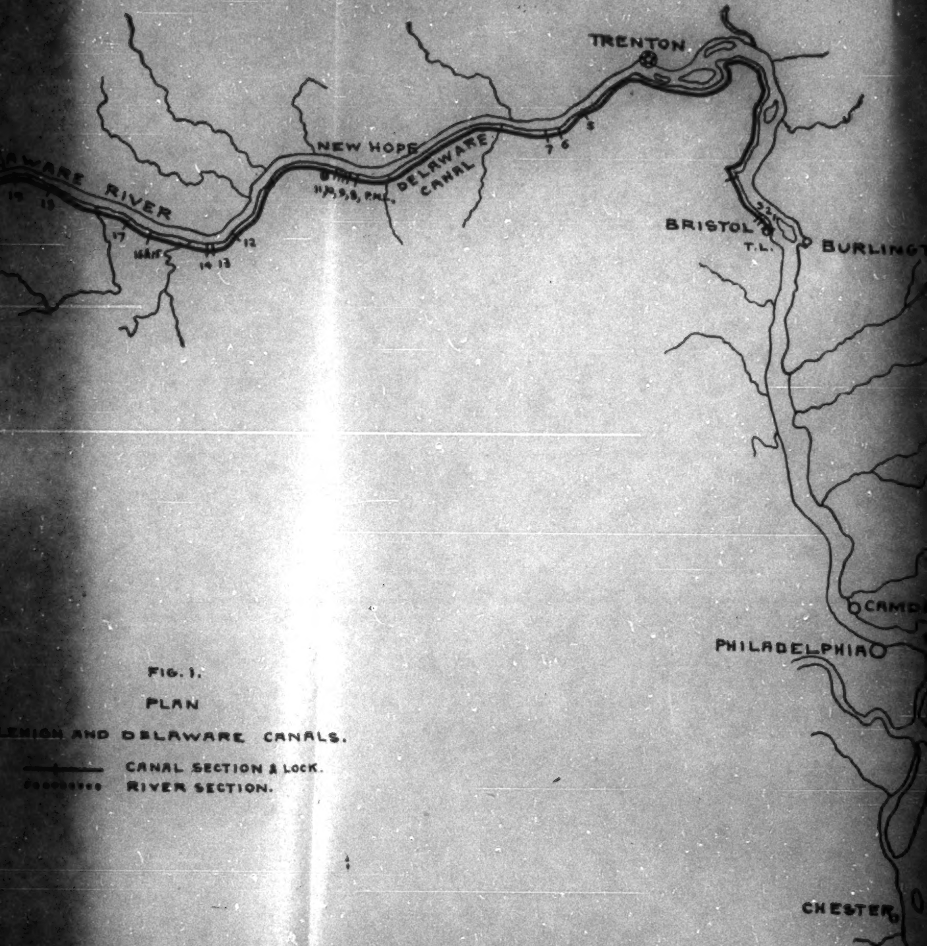

AWARE RIVER
19 18
17
16&15
14 13
12
NEW HOPE
11,10,9,8, P.H.L.
DELAWARE CANAL
7 6
5
TRENTON
3 2 1
BRISTOL
T.L.
BURLINGT
CAMD
PHILADELPHIA
CHESTER
CANAL SECTION & LOCK.
RIVER SECTION.

FIG. 1.

PLAN

LEHIGH AND DELAWARE CANALS.

not only by inspection but also very conclusively by the results of tests. In our comparative calculations of power required respectively by the locomotive and monorail systems, therefore, we have used the results obtained in using Tractor No. 3.

The tractors were operated upon a monorail supported at a height of 4 ft. above the ground by steel posts placed at intervals of 18 ft. The rail, as used in the installation at Mauch Chunk, is an ordinary 10-in. I-beam weighing 75 lb. to the yard. The monorail with supports and braces complete weigh 120 lb. per yard and is erected along the canal outside the tow-path. The construction is illustrated in Fig. 4.

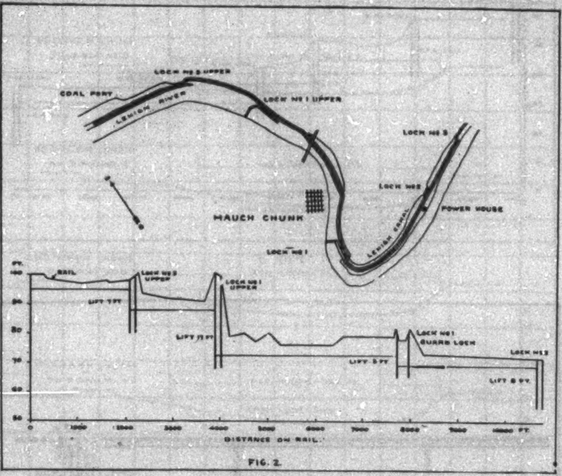

LOCK No 2 UPPER
COAL PORT
LEHIGH RIVER
LOCK No 1 UPPER
LOCK No 3
LOCK No 2
POWER HOUSE
MAUCH CHUNK
LEHIGH CANAL
LOCK No 1
FT.
100
90
80
70
60
50
RAIL
LOCK No 2 UPPER
LIFT 7 FT
LOCK No 1 UPPER
LIFT 11 FT
LOCK No 1 GUARD LOCK
LIFT 3 FT
LOCK No 3
LIFT 8 FT
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000 FT
DISTANCE ON RAIL.
FIG. 2.

FIG. 2

A fourth tractor, No. 4, built in Paris, was also subjected to certain tests. This machine, without testing crew and instruments, weighed 3,465 lb. It was equipped with one direct-current 500-volt motor of 15 h.p. The diameter of wheels was 12.75 in. and the wheel base 24 in. This machine is illustrated in Fig. 8.

For this smaller machine a section of monorail tract 1,200 ft.

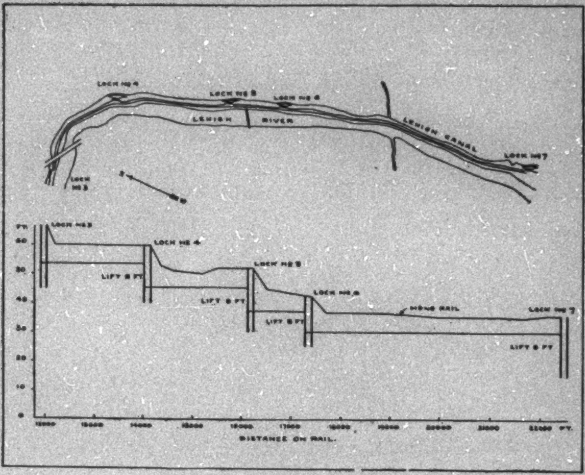

LOCK NO 4
LOCK NO 5
LOCK NO 6
LEHIGH RIVER
LEHIGH CANAL
LOCK NO 7
LOCK NO 3
FT.
60
50
40
30
20
10
0
LOCK NO 3
LOCK NO 4
LIFT 8 FT
LOCK NO 5
LIFT 8 FT
LOCK NO 6
LIFT 8 FT
MONO RAIL
LOCK NO 7
LIFT 8 FT
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000
22000 FT.
DISTANCE ON RAIL.

FIG. 3

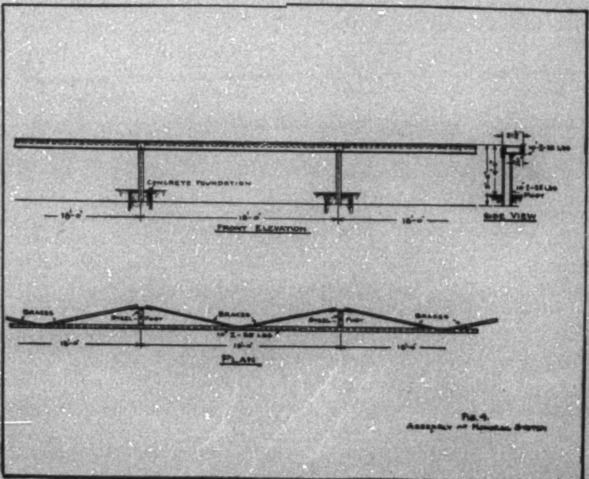

CONCRETE FOUNDATION
18'-0"
18'-0"
18'-0"
FRONT ELEVATION
SIDE VIEW
BRACES
STEEL POST
BRACES
STEEL POST
BRACES
PLAN
FIG. 4
ASSEMBLY OF MONORAIL SYSTEM

FIG. 4

long was erected on wooden posts between Locks Nos. 2 and 3. The rail in this case was a 7-in. I-beam, weighing 45 lb. per yard, and was erected at a height of 4 ft. from the ground. It was not deemed necessary to undertake complete tests of Tractor 4, as certain preliminary tests showed that the machine was not adequate in mechanical strength and power equipment for the service. Volt and ampere readings were made, however, in connection with dynamometer readings and from these the approximate performance of the machine was determined.

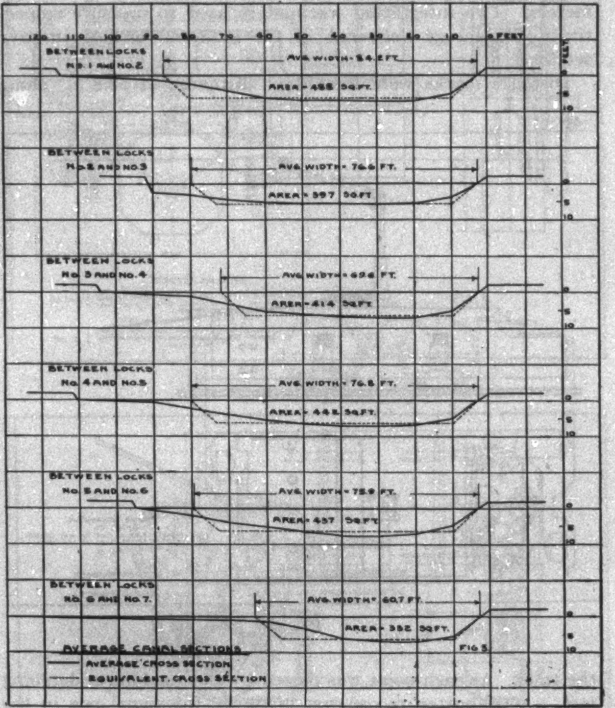


FIG. 5

The following instruments were used in making the tests:

Direct-current graphic recording wattmeter with time attachment. This wattmeter was also equipped with a signal pen used to record distances and special points by means of a push button. Weston ammeter. Weston voltmeter. Three spring dynamometers. Two integrating wattmeters used to measure respectively the energy delivered to the monorail and locomotive sections.

Distance marks were located at distances of 52.8 ft. along

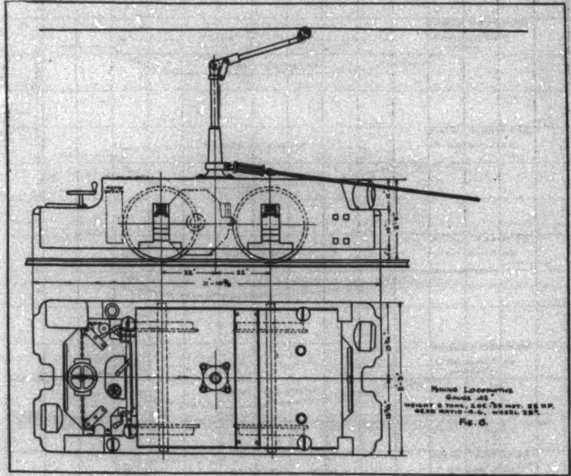


FIG. 6

the track. As each point was passed by the machine undergoing test, a push-button record was made by the signal pen in the graphic recording wattmeter and at the same instant the voltmeter and dynamometer were read by the test crew. In addition, during one complete run, the angle formed by the tow-rope and the center line of the track was determined at each distance point by measuring the distance from the center of the track to a fixed length of tow-line. All test results are corrected for this angle, and the tow-line pulls stated are the

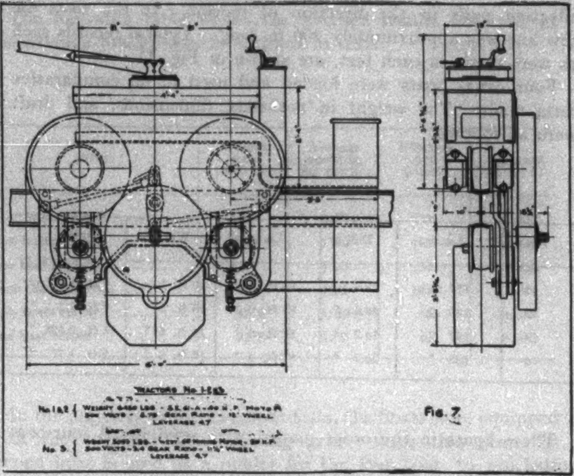

8"
8"
4'-4"
6'-0"
TRACTORS No. 1-2 & 3
No 1 & 2 { WEIGHT 6450 LBS. - G.E. 61-A - 40 H.P. MOTOR
500 VOLTS - 5.75 GEAR RATIO - 12" WHEEL
LEVERAGE 4.7
No. 3 { WEIGHT 5050 LBS. - WEST'G MOTOR - 30 H.P.
500 VOLTS - 3.4 GEAR RATIO - 11½" WHEEL
LEVERAGE 4.7
FIG. 7

FIG. 7

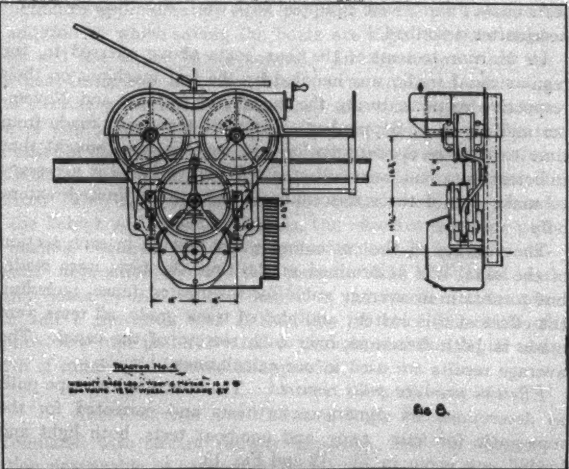

TRACTOR No. 4
WEIGHT 5488 LBS. - WEST'G MOTOR - 15 H.P.
500 VOLTS - 12¼" WHEEL - LEVERAGE 5.7
FIG. 8.

FIG. 8

effective pulls in the direction of motion. In the tests the tow-line was approximately 200 ft. long. Typical records such as were made in each test, are shown in Fig. 11.

Four canal boats were loaded and used in all comparative tests made. The weight in net tons, dimensions, and draft were as follows:

TABLE I

| Boat | Loaded | Empty | Length | Width | Draft |
|---|---|---|---|---|---|
| 1 | 137 tons | 23.5 tons | 87 ft. 6 in. | 10 ft. 5 in. | 5 ft. 1.875 in. |
| 2 | 139 " | 23.0 " | 87 ft. 6 " | 10 ft. 5 " | 5 ft. 2.5 " |
| 3 | 137 " | 24.2 " | 87 ft. 6 " | 10 ft. 5 " | 5 ft. 2.625 " |
| 4 | 135 " | 24.2 " | 87 ft. 6 " | 10 ft. 5 " | 5 ft. 1.75 " |

These boats in the order named were used in all four-boat tests.

Boats 3 and 4 were used in one-boat tests.

Boats 1 and 2 were used in two-boat tests. In the later tests boats 1 and 2 were equipped with the " Erie Steering Gear " hereinafter described.

In addition to tests of the four boats above referred to, the regular canal traffic was handled by the test machines on their respective sections during the months of October and November and a part of September. Complete tests were made from time to time as opportunity offered, until it was thought that sufficient data had been collected. We have found it necessary to make use of these miscellaneous tests to a limited extent only.

The velocity of the current of water flowing in each section of the canal was determined at the time the tests were made, but to obtain an average value for towing resistance, including the effect of this current and also of track grade, all tests were made in both directions over each section of the canal. The average results are used in our calculations.

*Effective tow-rope pulls required.* The effective tow-rope pulls as determined by dynamometer tests and corrected for the rope-angle for four-, two-, and one-boat tests, both light and loaded, are given in Fig. 12 and Fig. 13.

The following table shows the average results obtained at the average towage speeds attained in tests:

TABLE II

| Boats | Weight tons (2000 lb.) | Average speed in mi. per hr. | Effective pull pounds | Constant ($C V^2 T$) |
|---|---|---|---|---|
| **Four boats loaded** | 548 | 2.98 | 2200 | 0.452 |
| **Two boats loaded** | 274 | 3.62 | 1500 | 0.418 |
| **One boat loaded** | 137 | 4.00 | 1000 | 0.456 |
| **Four boats empty** | 95 | 4.00 | 1010 | 0.664 |
| **Two boats empty** | 47.5 | 4.20 | 560 | 0.668 |
| **One boat empty** | 23.8 | 5.00 | 400 | 0.673 |

In the majority of the two-boat tests, the boats were equipped with the so-called Erie steering gear. With this gear the second boat is used as a rudder for the first boat, to which it is tightly lashed. The arrangement is illustrated in Fig. 10.

The effect, so far as resistance of the water is concerned, is a reduction of approximately eight per cent. in the pull required; in addition to which saving the boats are kept in better alignment and are under better control. In the majority of the four-boat-tests, the first two boats were equipped with the Erie steering gear, but this beneficial effect as regards reduction of pull required, was apparently lost, owing probably to the effect of the drag of the last two boats, which tended to alter the position of the first two with reference to the line of motion.

From Table II it appears that for boats, such as are used on the Lehigh and Delaware canals, the effective tow-rope pull in pounds, required for any number of loaded boats, is expressed approximately by the formula $0.45 V^2 T$, and for empty boats by $0.67 V^2 T$, where $V$ is the speed in miles per hour and $T$ the total tons (2000 lb.). A brief discussion of required tow rope pull as related to draught and the depth and width of canal will be found in appendix.

### Acceleration and Maximum Rope Pulls

Compared with electric railway operation, the rate of acceleration practicable of attainment in towing canal boats is low.

Acceleration, however, is relatively unimportant, as the time of run is long compared with the time consumed in acceleration. The greatest pull is exerted when the last control-point is reached, but this does not greatly exceed the pull required at full running speeds.

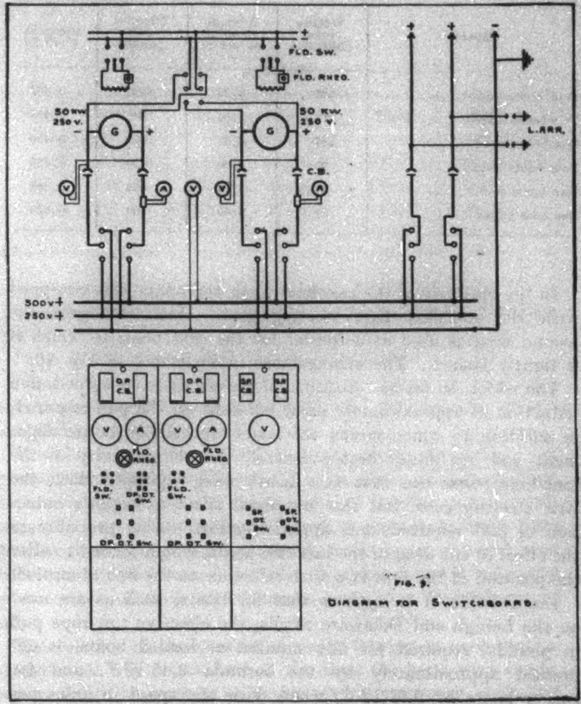

+
±
FLD. SW.
FLD. RHEO.
+
+
−
50 KW
250 V.
−
G
+
50 KW.
250 V.
−
G
+
C.B.
V
A
V
V
A
L.ARR.
500V+
250V+
−
O.P.
C.B.
O.P.
C.B.
S.P.
C.B.
S.P.
C.B.
V
A
V
A
V
FLD.
RHEO
FLD.
RHEO
FLD.
SW.
DP. DT.
SW.
FLD.
SW.
S.P.
DT.
SW.
S.P.
DT.
SW.
DP. DT. SW.
DP. DT. SW.
FIG. 9.
DIAGRAM FOR SWITCHBOARD.

FIG. 9

Table III gives the maximum and average results obtained in four-, two-, and one-boat tests, both loaded and empty.

TABLE III.—Acceleration and Rope Pull

(Pulls not corrected for rope angle.)

| | Acceleration miles per hr. per sec. | | Pull lb. at end of acceleration | | Average pull lb. running | |
|---|---|---|---|---|---|---|
| | Ave. | Max. | Ave. | Max. | Ave. | Max. |
| 4 boats loaded | 0.0243 | 0.045 | 2370 | 3100 | 1990 | 2300 |
| 4 boats empty | 0.0975 | 0.142 | 1220 | 2100 | 1040 | 1250 |
| 2 boats loaded | 0.0594 | 0.101 | 2240 | 3100 | 1500 | 1700 |
| 2 boats empty | 0.0995 | 0.135 | 850 | 1150 | 680 | 1100 |
| 1 boat loaded | 0.0667 | 0.103 | 1190 | 1800 | 650 | 1000 |
| 1 boat empty | 0.1090 | 0.173 | 730 | 1100 | 625 | 900 |

## Towing Machines Tested.

In most of our tests Mining Locomotive 15 and Tractors 1 and 3 were used. Comparison was made at speeds and effective pulls as nearly identical as was found practicable.

As to meet these conditions the various machines tested required different operating energy, and as change in the energy affected the motor efficiency, the electric losses in the motors in all cases have been deducted from the kilowatt input in determining the mechanical efficiency of the machines. The mechanical loss of the motors and gears in each case is charged against the respective machines. The tow-line pull in all cases has been corrected to the effective pull in pounds in the direction of motion. Results are given in Table IV.

TABLE IV

Efficiency of Towing Machines

| | Effective pull 1000 lb. | Effective pull 2000 lb. | Effective pull 3000 lb. |
|---|---|---|---|
| Mining Locomotive | 80% | 83.5% | 84% |
| Tractor 1 | 68 | 73.3 | 74.8 |
| Tractor 3 | 73 | 77.2 | 77.5 |

Expressed in another way the results are summarized in Table V.

The results of these tests are perhaps more clearly illustrated in Fig. 14, in which the inputs to the towing machines are reduced to equivalent draw-bar pulls.

The performance of the three towing machines, running light without load, is shown in Table VI. For convenience, the input to the machines is expressed both in kilowatts and equivalent draw-bar pull in pounds. The values stated include all mechanical friction of motors, gears, and track, but do not include the electrical losses in the motors.

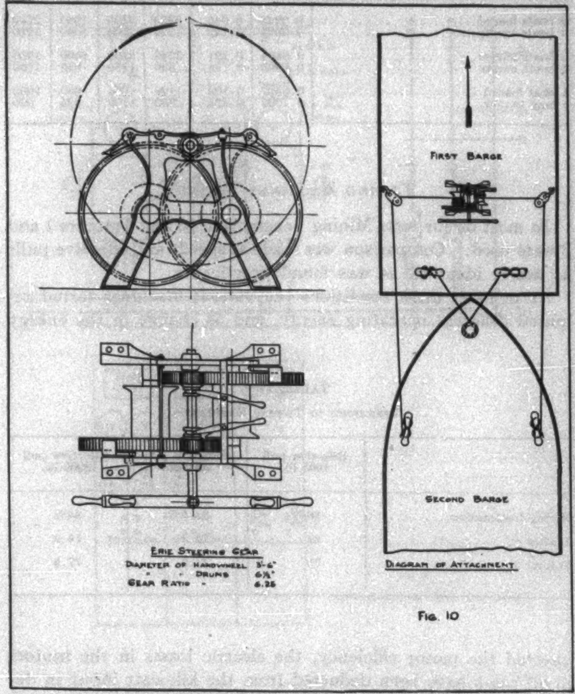
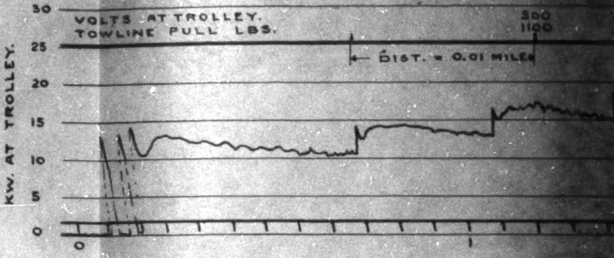

First Barge
Second Barge
Erie Steering Gear
Diameter of Handwheel 3'-6"
" " Drums 6½"
Gear Ratio - 6.25
Diagram of Attachment
Fig. 10

FIG. 10

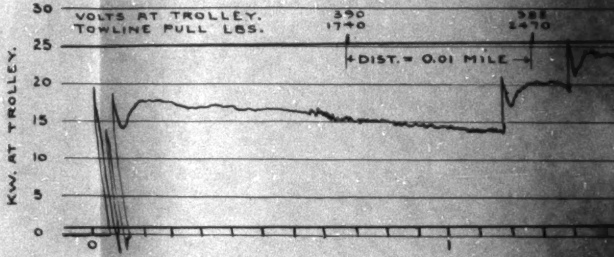
TRACTOR Nº 3.

EN LOCKS 4-5 DOWN.
TOW, WEIGHT 548 TONS.
H OF TOWLINE 200 FT.
NGLE OF TOWLINE 13°.
VELOCITY OF WATER 0.
DRY, WIND S.W. LIGHT.
131, NOV. 3 1907.



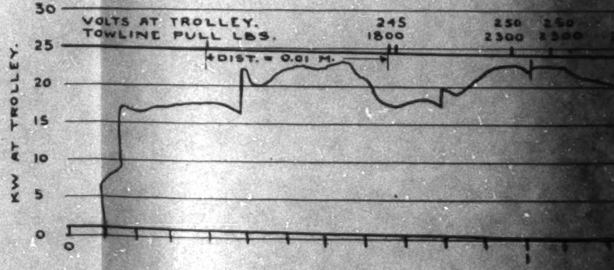
TRACTOR Nº 1.

EEN LOCKS 4-5 DOWN.
T TOW, WEIGHT 548 TONS.
TH OF TOWLINE 200 FT.
ANGLE OF TOWLINE 13°.
VELOCITY OF WATER 0.
DRY, WIND N.W. LIGHT.
Nº 58, OCT. 13 1907.



MINING LOC. Nº 15.

EEN LOCKS 2-1 UP.
T TOW, WEIGHT 274 TONS.
H OF TOWLINE 180 FT.
NGLE OF TOWLINE 15°.
VELOCITY OF WATER 0.58 MPH.
DRY, WIND W. LIGHT.
Nº 82, OCT. 22 1907.



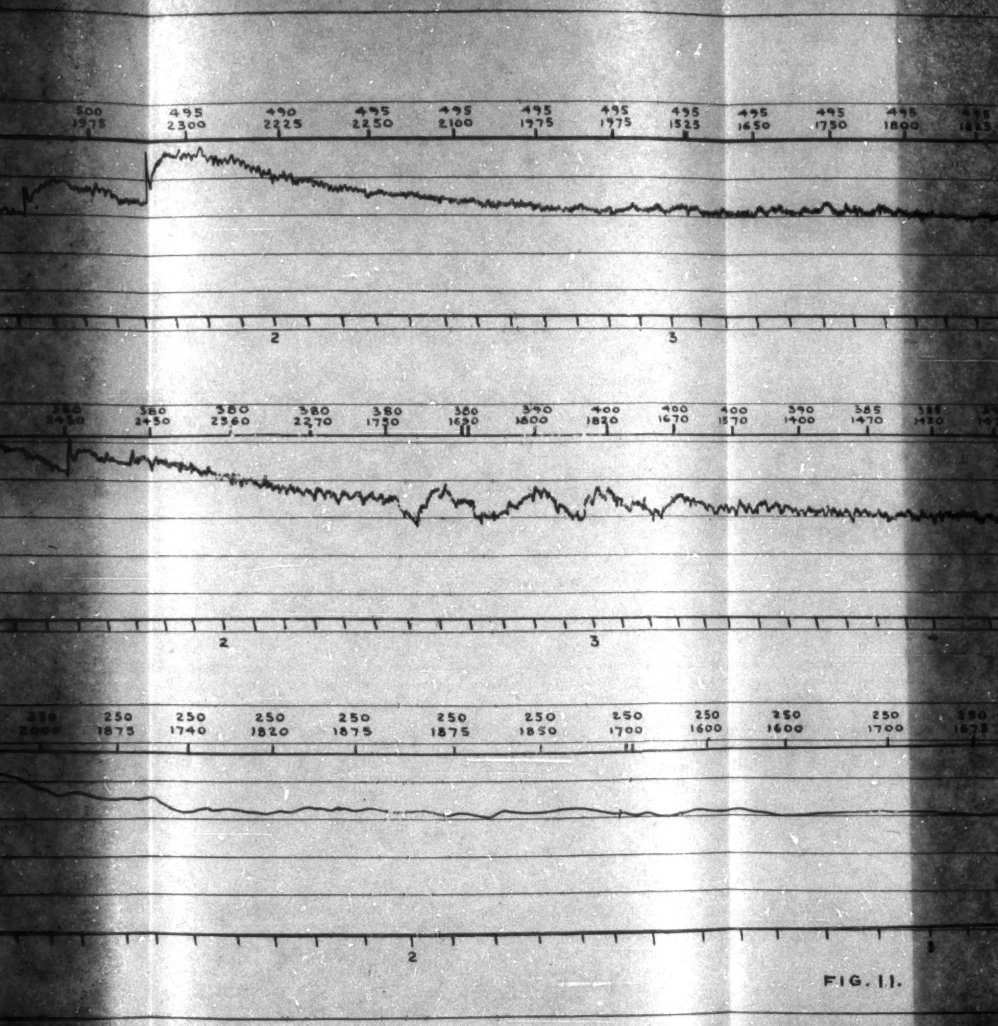

500
1975
495
2300
490
2225
495
2250
495
2100
495
1975
495
1975
495
1525
495
1650
495
1750
495
1800
495
1825
2
3
380
2450
380
2450
380
2560
380
2270
380
1750
380
1690
390
1800
400
1820
400
1670
400
1570
390
1400
385
1470
385
1420
2
3
250
2000
250
1875
250
1740
250
1820
250
1875
250
1875
250
1850
250
1700
250
1600
250
1600
250
1700
250
1675
2

FIG. 11.

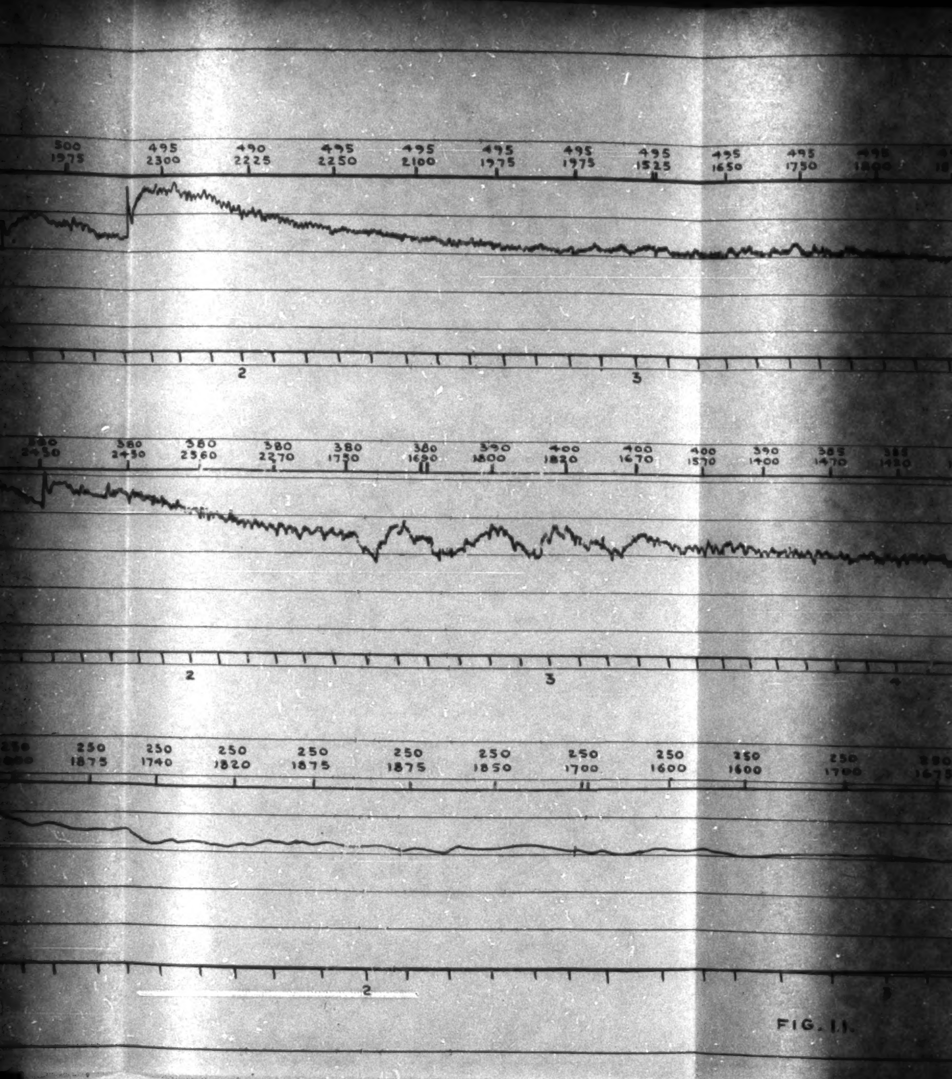
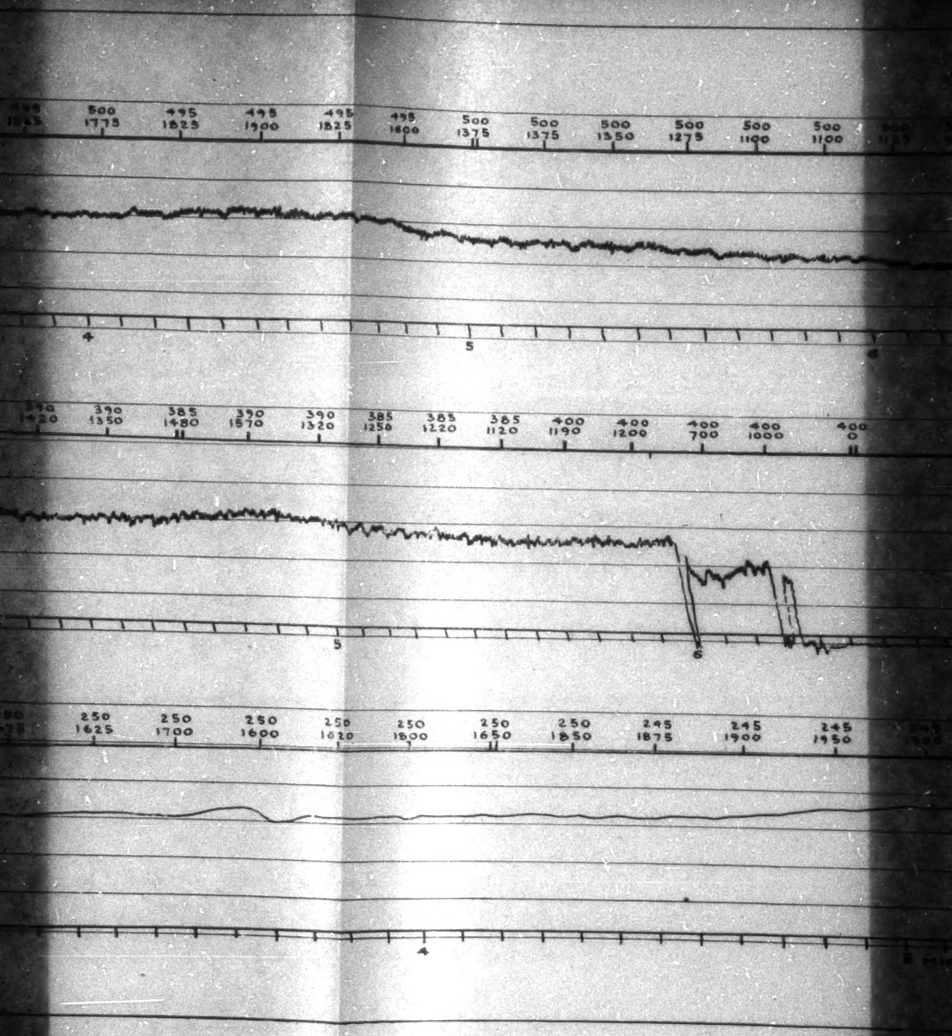

500 1975
495 2300
490 2225
495 2250
495 2100
495 1975
495 1975
495 1525
495 1650
495 1750
495 1800
2
3
380 2450
380 2450
380 2560
380 2270
380 1750
380 1690
390 1800
400 1820
400 1670
400 1570
390 1400
385 1470
385 1420
2
3
4
250 1875
250 1740
250 1820
250 1875
250 1875
250 1850
250 1700
250 1600
250 1600
250 1700
250 1675
2

FIG. 11.


500
1775
495
1825
495
1900
495
1825
495
1600
500
1375
500
1375
500
1350
500
1275
500
1100
500
1100
4
5
6
390
1420
390
1350
385
1480
390
1570
390
1320
385
1250
385
1220
385
1120
400
1190
400
1200
400
700
400
1000
400
0
5
6
250
1625
250
1700
250
1600
250
1620
250
1800
250
1650
250
1850
245
1875
245
1900
245
1950
4

### TABLE V

**Equivalent Pull in Pounds Lost in Machine and Track Friction when Delivering**

| | Effective pull 1000 lb. | Effective pull 2000 lb. | Effective pull 3000 lb. |
|---|---|---|---|
| Mining Locomotive | 250 | 400 | 590 |
| Tractor 1 | 450 | 700 | 1000 |
| Tractor 3 | 375 | 600 | 890 |

### TABLE VI

| Speed miles per hour | Mechanical Friction Running Light | | | | | |
|---|---|---|---|---|---|---|
| | Kilowatts | | | Equivalent drawbar pull pounds | | |
| | Mining Loco. | Tractor 3 | Tractor 1 | Mining Loco. | Tractor 3 | Tractor 1 |
| 3 | 0.88 | .98 | 1.44 | 148 | 164 | 242 |
| 4 | 1.28 | 1.40 | 2.16 | 161 | 176 | 272 |
| 5 | 1.70 | 1.82 | 2.90 | 171 | 183 | 292 |
| 6 | 2.17 | 2.32 | 3.68 | 182 | 195 | 308 |
| 8 | 3.20 | 3.41 | .... | 201 | 214 | ... |
| 10 | 4.40 | .... | .... | 221 | ... | ... |

The results of these tests are illustrated in Fig. 13.

It will be noted that in running without load the machines preserve relatively the same relationship as they do when operating under load conditions, though the relative magnitude of the values are changed. When developing large draw-bar pulls, the mechanical losses in Tractor 3 are 50 per cent. in excess of those of the Mining Locomotive. Mechanical losses in Tractor 1 exceed those of the Mining Locomotive by from 70 to 80 per cent. Under light running conditions these excess losses are reduced to about 7 per cent. in the case of Tractor 3, though the excess remains approximately 70 per cent. for Tractor 1.

The running light losses are, in themselves, relatively unimportant, as the amount of power required is small and the amount of idle running relatively very small; but, as showing errors in design and workmanship, which extend their influence to conditions of heavy load, they are important. We shall not here enter into a theoretical discussion of the design of these Tractor machines. It is apparent that their mechanical design can be improved materially. When running light, it would be reasonable to expect that these machines, if properly designed, should effect a saving in power consumed almost

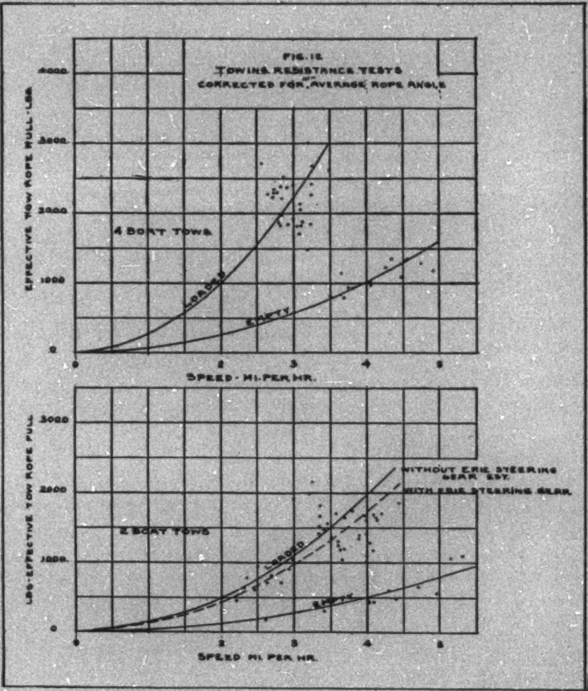


FIG. 12

proportional to their less weight as compared with the Mining Locomotive.

Under load conditions, especially as the draw-bar pull approaches the maximum of which the locomotive is capable, the latter machine, theoretically, should show the higher mechanical efficiency. This is due to the fact that when the Mining Locomotive utilizes its entire weight for traction; to obtain a similar draw-bar pull with the Tractor, the two driving wheels on top must have a pressure upon them equal to the weight of the Mining Locomotive. As the weight of the Tractor is 10,000 lb. less than that of the Mining Locomotive, a pressure of at least

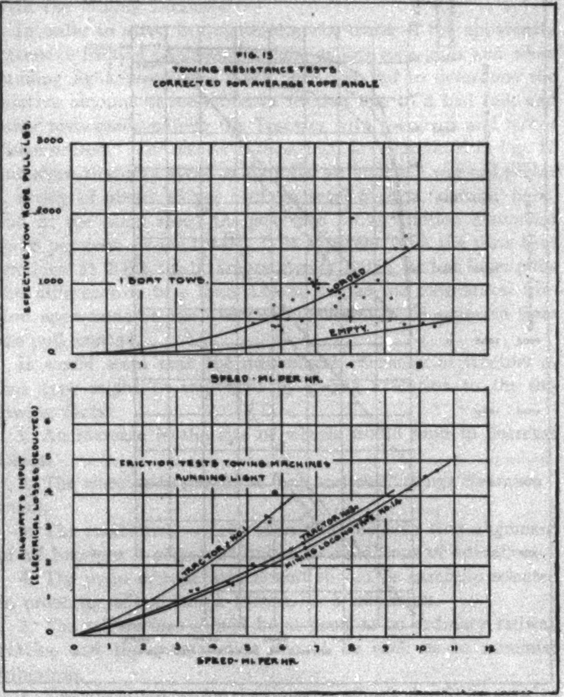


FIG. 13

10,000 lb. must be exerted on the lower or pressure wheels. It is evident, therefore, that the track and rolling friction of the Tractor must be greater than that of the Mining Locomotive by the amount of this excess pressure on the track. Considering track friction only, this excess should amount to about 60 per cent. at maximum pull. The tests of Tractor 3 show an excess of about 50 per cent. at 3,000 lb. rope pull, though the test results are not exactly comparable, as motor and gear frictions are included and are different in the two machines.

Assuming that the Tractor may be so designed that its aggregate mechanical friction per ton of weight does not exceed that of the Mining Locomotive, it is obvious that when running light less power should be required to move the former at a given speed than is required by the latter. Assuming good mechanical design, it follows that the Tractor under light loads

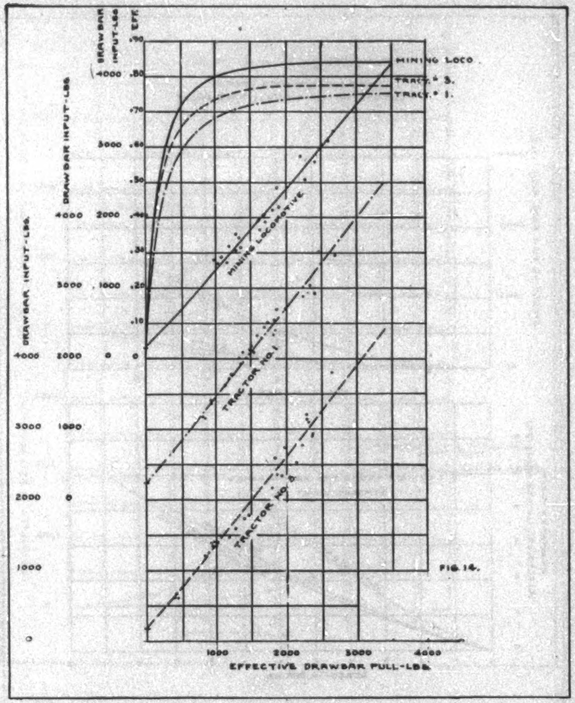


FIG. 14

should be more efficient than the Mining Locomotive, and that at some load between the limits of very light load and full load, the efficiency curves of the two machines should cross. So far as comparative efficiency is concerned, therefore, great care must be taken in designing the Tractor, to minimize friction losses if it is expected to make a good showing as compared with the Mining Locomotive.

In order to assist in determining the cause of the apparently excessive friction of these Tractors, at low rope-pulls and when running light, tests were made on a wet rail to determine the relative amount of reduction in friction due to a bad rail, and other tests made pulling the Tractors with the gears and motor disconnected. The results of these tests are illustrated in Fig. 15 and show that at a speed of six miles an hour the wet rail effects a saving of about 16 per cent. in total friction, running light, and at the same speed the gear and motor friction amounted to 28 per cent. of the total. It is apparent from the tests that frictions at light loads are relatively small and at large pulls the difference is to a large extent lost as the mechanical friction approximates the theoretical amount to be expected from the pull exerted.

It would seem that the mechanical efficiency of tractors of this type might be improved by giving attention to the following facts:

1. An increase in the size of wheels would tend to decrease losses.

2. The wheel-base should be long and the " flange clearance " small.

3. The mechanical construction must be such that alignment of all bearings is preserved under all conditions of operation.

4. The point of rope attachment should be carefully selected in order to reduce flange friction to a minimum.

5. The rail surface should be as good as on ordinary railway tracks, and the construction should be such as to minimize vibration.

6. The use of guides for the pressure wheels should be avoided if practicable. If used, the vertical motion in the guides for the pressure wheels should be free.

7. The pressure wheels should have no flange.

8. Arrangements for oiling the bearings of tractors as well as of locomotives should follow railroad practice.

*Speed limitations and length of tow.* **In hauling canal boats** by mules, the speeds attained vary from 1.25 to 2 miles an hour. When the current assists, the speed exceeds these amounts; when the tow is against the current, the speed sometimes drops very low. Dynamometer tests were made, and it was determined that in starting a tow, a team of good mules could exert momentary pull approximating 800 lbs. This is maintained but momentarily.

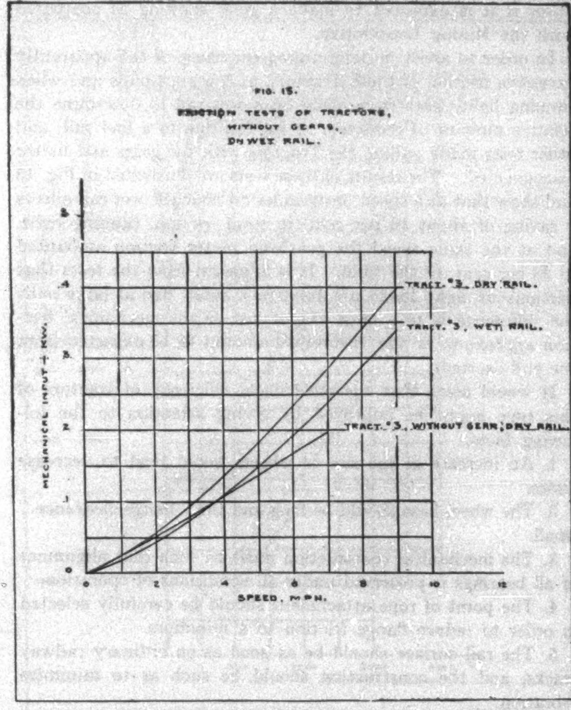


FIG. 15

The average speed at which a team of mules draws a one-boat tow approximates 1.75 miles an hour and does not exceed 2 miles an hour in still water. The pull required at 2 miles an hour, as determined by the tests in which the Mining Locomotive and Tractors were used, is 250 lb.; at 1.75 miles an hour it is 190 lb., and at 1.5 miles an hour it approximates 140 lb. The curves expressing the relation of pull and speed for tows of various length are shown in Fig. 16.

Tests were made to determine the practicable limits of speed when towing is done with towing machines. These limits depend upon the following:

*a.* Ability to steer the boats.

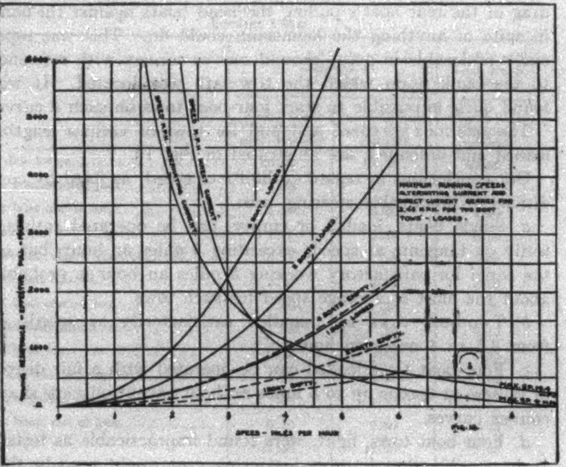


FIG. 16

*b.* Wash of canal banks.

*c.* Time required for locking.

*d.* Tonnage capacity and length of tow.

The selection of a best speed depends also upon the number of boats which must pass through the canal in a given time to handle its business. This will be referred to further under the heading "*Tonnage Capacity and Length of Tow*".

*Ability to steer boats.* Single boats, both loaded and empty, were tested at speeds slightly exceeding 5 miles an hour and no difficulty was experienced in steering them.

Two-boat tows loaded were operated at speeds up to 4.5 miles an hour. With the Erie steering gear the boats handled well at this speed, but care had to be exercised by the helmsman to keep his course true. Two-boat tows (light) were operated successfully at a speed of 5.3 miles an hour.

Four-boat tows (loaded), the first two boats being equipped with the Erie steering gear, were operated at a speed of 3.5 miles an hour. At this speed, however, it was necessary for the helmsman to exercise great care to prevent the boats yawing. Four-boat tows, empty, were operated at speeds up to 5 miles an hour, but great difficulty was experienced in steering; the drag of the rear boat's pulling the head boats against the bank in spite of anything the helmsman could do. This was especially noticeable in going around curves convex with reference to the bank upon which the tow-path was located. It was found quite impossible to start four-boat tows on such a curve.

The relations of speed and pull for tows of various lengths, loaded and unloaded, are illustrated in Fig. 16.

Our conclusions in regard to limits of speed, as fixed by conditions of practicable steering, are:

*a.* Single boats, loaded or empty, can be operated satisfactorily on tangents at speeds exceeding 5 miles an hour, but on the canal for satisfactory working 5 miles an hour is probably about the limit of average speed for such tows.

*b.* Two-boat tows are handled satisfactorily at speeds of from 3.5 to 4 miles an hour.

*c.* Four-boat tows loaded can be operated with a fair degree of success at speeds up to 3 miles an hour except on very sharp convex curves.

*d.* Four-boat tows, light, were found impracticable as tested. It is possible that improved steering gear might remedy the difficulties encountered, except that no conceivable steering-gear would make it possible to handle four-boat tows, light, in a heavy wind.

*Wash of canal banks.* At the higher speeds covered by the tests a tendency to cause wash of the canal banks was noted. The tests were not of sufficient duration to justify an attempt at estimating the relation of wash and speed.

At a given speed the wash is greatest in shallow and narrow sections of the canal. To a certain extent in these sections the speed is automatically regulated; the resistance to the passage of the boat being increased and this resistance immediately reacting upon the series motor used in our tests.

The speed of towing should be under the control of the operator, and to obtain best results the motor used should be capable of operating at any desired speed within the predetermined maximum limits. With equipment of this character, the speed can be regulated on those sections where the wash might otherwise be injurious.

*Time required for locking.* Tests were made to determine the time required in locking one, two and four boats and to see if the time could be reduced in any way. The following is a typical locking for two- or four-boat tows under test conditions.

TABLE VII
LOCKING TESTS

| | Lift 8 ft. Lock No. 4 4 boats | | Lift 8 ft. Lock No. 5 2 boats |
|---|---|---|---|
| | First 2 boats Erie steering-gear, minutes | Second 2 boats No gear minutes | First 2 boats Erie gear, minutes |
| Tow-line let go | 00.00 | 00.00 | 00.00 |
| First boat entered lock | 1.75 | .... | .... |
| First boat tied in lock | 1.25 | 3.00 | 2.00 |
| Second boat tied in lock | 1.75 | 3.75 | 3.50 |
| Upper gate closed (lock emptied) | 0.75 | .25 | 1.00 |
| Lower gate opened | 2.00 | 3.50 | 3.00 |
| First boat started out | .00 | .25 | .00 |
| Second boat started out | 1.75 | .25 | 0.75 |
| First boat out | 0.25 | 1.25 | 0.25 |
| Steering-gear adjusted | 2.00 | 1.00* | 1.50 |
| Started pulling both boats | .00 | 1.25 | .... |
| Both boats out of lock | 0.50 | 0.50 | 0.25 |
| | 12.00 | 15.00 | 12.25 |
| Lower gate shut | .50 | .... | 1.00 |
| Upper gate opened | 2.00 | .... | 1.75 |
| | 2.50 | | 2.75 |

* Boats tied together only, no steering-gear.

SUMMARY

| | | |
|---|---|---|
| First two boats | 12.00 | minutes |
| Refilling lock | 2.50 | " |
| Second two boats | 15.00 | " |
| Total four-boat tow | 29.50 | |

The foregoing figures represent average results obtained in tests. During these tests the men handling the boats were working at a speed which they could not be expected to attain in normal service and, therefore, we have based upon the test results estimates of the average time of locking to be expected in ordinary working.

The actual time, as determined by test and our estimate for average conditions, (the latter of which is used in subsequent calculations) is given below:

TABLE VIII

| Time locking two-boat locks | Observed test time | Estimated average time |
|---|---|---|
| Time locking four boats | 29.5 min. | 35 min. |
| Time locking two boats | 12.0 " | 15 " |
| Time locking one boat | 8.0 " | 10 " |

In four-boat locks, with the first two boats and the last two boats equipped with Erie steering-gear, it would not be necessary to disconnect the steering-gear and the time of locking would not greatly exceed that for two boats. An estimate of 20 minutes we think is conservative.

No actual tests of the single-boat locks on the Delaware canal were made using canal boats, but during a trip of inspection the time of all lockings of the launch used were taken, and from these observations the time of locking for canal boats was estimated as follows:

TABLE IX

| | | |
|---|---|---|
| Coasting into lock, tests 4 and 5 | 2.75 | minutes |
| Upper gate up (average on trip) | .50 | " |
| Lower gate opened (average on trip) | 1.75 | " |
| Boat out, average of tests | 1.50 | " |
| | 6.50 | |
| Time refilling lock and opening gate | 2.75 | " |
| Add for second boat | 6.50 | " |
| Adjust steering gear | 2.00 | " |
| Two boat tow, total time | 17.75 | " |
| Estimated average time | 21.00 | " |

The following table gives the estimated average time for locking with tows of different lengths and with locks of different size as used in our calculations.

TABLE X

| | 1 boat lock | 2 boat lock | 4 boat lock |
|---|---|---|---|
| Time locking four boats | 45 | 35 | 20 |
| Time locking two boats | 21 | 15 | 12 |
| Time locking one boat | 8 | 10 | 11 |

The following table gives the estimated time spent in locking from Coalport to Bristol for tows of different lengths based upon the above estimates of time required per lock. (There are 1 four-boat locks and 47 two-boat locks on the Lehigh Canal and 10 two-boat locks and 12 one-boat locks on the Delaware Canal.)

TABLE XI

| | |
|---|---|
| Four-boat tows, hours one way | 42.6 hours |
| Two-boat tows, hours one way | 18.7 " |
| One-boat tows, hours one way | 11.3 " |

*Conclusions.* The following is a tabulation of the speeds recommended for tows varying from one to four boats, loaded and empty, assuming, (*a*), that direct-current series motors are employed, and, (*b*), that single-phase alternating-current motors of the compensated type be used.

TABLE XII
MAXIMUM SPEED BETWEEN LOCKS

| | Direct current | Alternating current |
|---|---|---|
| Four boats loaded | 3.00 | 2.88 |
| Four boats empty | 4.00 | 4.20 |
| Two boats loaded | 3.45 | 3.45 |
| Two boats empty | 4.60 | 5.00 |
| One boat loaded | 4.00 | 4.20 |
| One boat empty | 5.30 | 6.00 |

Our conclusions in respect to speeds are based upon the observed facts as regards ability to steer boats, the wash of canal banks, the relative time required in locking, and between locks and the tonnage capacity of the canal as affected by the length of tow.

The speeds recommended for direct-current and alternating-current motor equipment respectively, differ by reason of the different speed characteristics of the motors of these respective types. The speed characteristic of the direct-current motor used is that of the series motor on Tractor 1 as used during the tests. The speed characteristics of the alternating-current motor are those of a typical series, compensated, 25-cycle motor. In Fig. 16 the speed curves of these two motors are plotted upon the assumption that the gear-ratios selected are such as will give the same speed for the two contrasted equipments in pulling a tow of two loaded boats, the length of tow being that which,

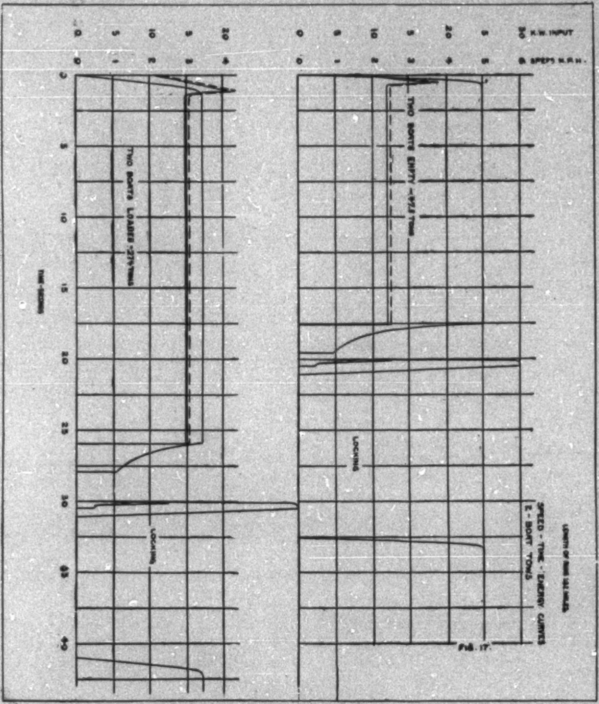


FIG. 17

from a purely physical consideration of the problem, appears best.

We have assumed the same speed characteristics of electrical equipment in comparing the mining locomotive with the tractors. The motors with which these respective machines were equipped during tests did not have identical speed characteristics; but there is no reason why they could not be so designed, and the assumption simplifies the general comparison with two types of towing machines.

*Tonnage capacity and length of tow.* As the length of tow limits the practicable running speed and determines the time consumed in locking, the length of the tow directly affects the tonange capacity of the canal. The maximum running speeds described above, and shown graphically in Fig. 16, give average running speeds which were determined from speed-time curves as shown in Fig. 17. The following table gives the average time required for four-, two-, and one-boat tows to make the round trip from Coalport to Bristol loaded and return empty.

TABLE XIII

TIME IN TRANSIT OVER ENTIRE CANAL—106.2 MILES, WITH EXISTING LOCKS

| System of Operations<br>Number of boats in tow | Direct current | | | Alternating current | | |
|---|---|---|---|---|---|---|
| | Four boats | Two boats | One boat | Four boats | Two boats | One boat |
| Time locking, down | 42.6 | 18.7 | 11.3 | 42.6 | 18.7 | 11.3 |
| Time between locks, down | 34.8 | 30.2 | 25.8 | 36.3 | 30.2 | 24.6 |
| Time locking, up | 42.6 | 18.7 | 11.3 | 42.6 | 18.7 | 11.3 |
| Time between locks, up | 25.8 | 22.5 | 19.4 | 24.9 | 20.6 | 17.1 |
| Add 10% contingencies | 14.2 | 8.9 | 7.2 | 14.6 | 8.8 | 6.7 |
| Total in transit, round trip | 160.0 | 99.0 | 75.0 | 161.0 | 97.0 | 71.0 |

In order to handle a definite amount of freight, it is evident that a definite number of boats will have to pass through the canal, whether they are operated in four-, two-, or one-boat tows. The number of boats required for this service, however, will be proportional to the time required for a round trip. With a fixed amount of freight to be handled, therefore, it is evident that fewer boats will be required with one-boat tows on account of the higher average speed. The number of towing machines required for the service is proportional to the round trips required and the time for the round trip.

Table XIV shows the ratio of boats required and towing machines required for a definite traffic with tows of different lengths and locks as now existing on the canal:

TABLE XIV
RATIO BOATS AND TOWING MACHINES REQUIRED

| | Direct current | | | Alternating current | | |
|---|---|---|---|---|---|---|
| | Four-boat tows | Two-boat tows | One-boat tows | Four-boat tows | Two-boat tows | One-boat tows |
| Boats required... | 2.25 | 1.39 | 1.05 | 2.27 | 1.36 | 1.00 |
| Machines required | 0.56 | 0.70 | 1.05 | 0.57 | 0.68 | 1.00 |

The ultimate capacity of the canal is limited by the time required in locking. Table XV expresses the ratio of the ultimate capacities with four-, two-, and one-boat tows. Since boats are moving in both directions, the interval between tows is double the maximum time required in passing through that lock on the canal which requires the maximum time for the towing unit employed. We have prepared this table :

*a.* On the basis of locks as now existing,
*b.* All one-boat locks changed to two-boat locks.
*c.* All locks changed to four-boat locks.

TABLE XV
MAXIMUM TRAFFIC CAPACITY

| | Four-boat tows | Two-boat tows | One-boat tows |
|---|---|---|---|
| *Existing locks.* | | | |
| Minimum interval between tows........ | 90 min. | 42 min. | 22 min. |
| Ratio maximum capacity.............. | 0.98 | 1.05 | 1.00 |
| *One, changed to two-boat locks.* | | | |
| Minimum interval between tows........ | 70 min. | 30 min. | 22 min. |
| Ratio maximum capacity.............. | 1.25 | 1.47 | 1.00 |
| *All four-boat locks.* | | | |
| Minimum interval between tows........ | 40 min. | 24 min. | 22 min. |
| Ratio maximum capacity.............. | 2.20 | 1.83 | 1.00 |

On the Delaware Canal, where there are now 12 single locks, there is practically no gain in capacity by increasing the length of the tow. On the Lehigh Canal the capacity is increased nearly 50 per cent. by using two-boat tows, but only 25 per cent. with four-boat tows. The conversion of all the locks on both canals to four-boat locks would approximately double the capacity.

*Power required.* Speed-time curves have been constructed for both the mining locomotive and the tractor for the towing speeds selected as most practicable and described under the caption "*Conclusions*" for both single-phase alternating-current motors and direct-current motors. The general character of these curves is illustrated in Fig. 17 for a two-boat tow over an average run of 1.516 miles. The towing machines as tested were not equipped with motors suitably geared for the speeds desired. We have therefore, assumed these towing machines to be equipped with motors of suitable size and speed and possessing the same efficiencies at their rated loads as the motors furnished by

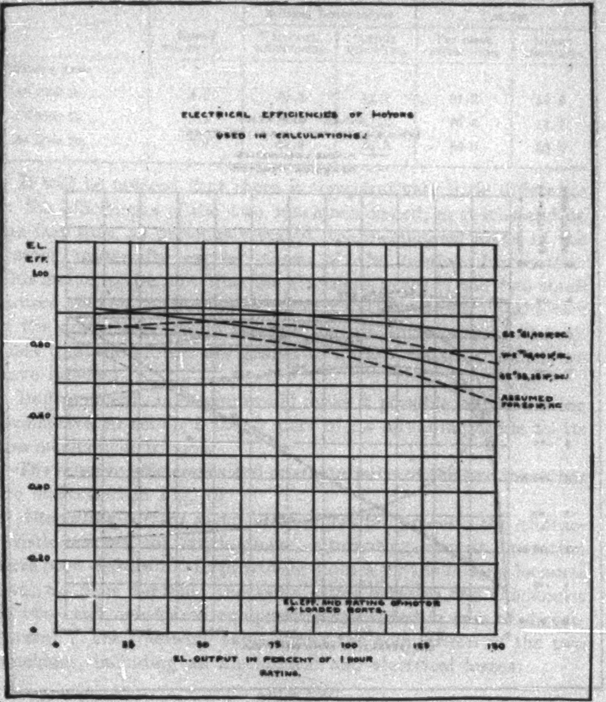


FIG 18

the manufacturers. The motor efficiencies are shown in Fig. 18. These efficiencies have been applied to the mechanical efficiencies of the towing machines, as shown in Fig. 14. We have so applied these efficiencies that the input for a four-boat tow

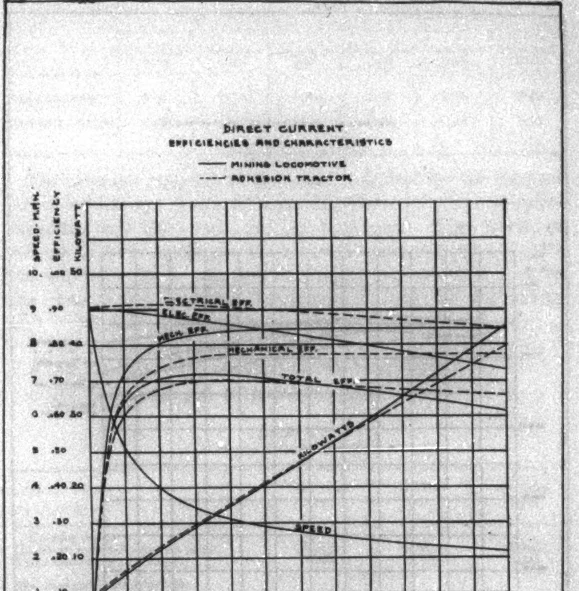


FIG. 19

(loaded) at the speed selected, will be 75 per cent. of the one-hour rating of the motor. The speed selected for both direct-current and alternating-current also corresponds to the speed recommended for two-boat tows. As already pointed out, this gives approximately the desired speeds for other tows.

*Direct-current motors.* The total efficiencies, kilowatt input at trolley, and speeds for the mining locomotive and tractor are given below. The efficiencies and inputs include all mechanical and electrical losses:

TABLE XVI

| | Speed mi. per hr. | Mining Locomotive | | Tractor | |
|---|---|---|---|---|---|
| | | Per cent. efficiencies | Input kilowatts | Per cent. efficiencies | Input kilowatts |
| Effective pull, | | | | | |
| At 1000 lb. | 4.0 | 70.2 | 11.3 | 67.2 | 11.8 |
| At 2000 lb. | 3.1 | 71.6 | 17.3 | 70.0 | 17.7 |
| At 3000 lb. | 2.7 | 69.5 | 23.3 | 69.0 | 23.5 |

It will be noticed that there is comparatively little difference in the efficiencies of the two machines tested, notwithstanding the fact that, as previously stated, the mechanical losses of the tractor materially exceed those of the mining locomotive. This is due to the fact that the electrical losses of the two small motors used on the mining locomotive exceed the electrical losses in the single large motor used on the tractor; assuming in both cases that the motors are geared to obtain the speed which we have selected.

Improvements in design would make it possible for the mining locomotive to retain a larger part of its advantage, due to its less mechanical friction.

The relative efficiencies and characteristics of the two machines are illustrated in Fig. 19.

*Alternating-current motor.* By a similar process, the characteristic curves for single-phase, alternating-current operation have been deduced. In providing motors for the mining locomotive, we have assumed the same ratios between the efficiencies of two- and one-motor equipments as existed in case of direct-current. The following table shows the comparison of the two machines, including all mechanical and electrical losses:

TABLE XVII

| | Speed mi. per hr. | Mining Locomotive | | Tractor | |
|---|---|---|---|---|---|
| | | Per cent. efficiencies | Input kilowatts | Per cent. efficiencies | Input kilowatts |
| Effective pull, | | | | | |
| At 1000 lb. | 4.3 | 66.8 | 13.0 | 64.5 | 13.4 |
| At 2000 lb. | 2.9 | 68.4 | 17.0 | 67.0 | 17.3 |
| At 3000 lb. | 2.3 | 67.2 | 21.2 | 66.5 | 21.5 |

The respective characteristics of the two machines are also shown in Fig. 20.

The average efficiency of the mining locomotive is about 1.5 per cent. higher than that of the tractor both with alternating-current and direct-current equipment and the average efficiency at the trolley is about 2.8 per cent. higher with direct-current than with alternating-current.

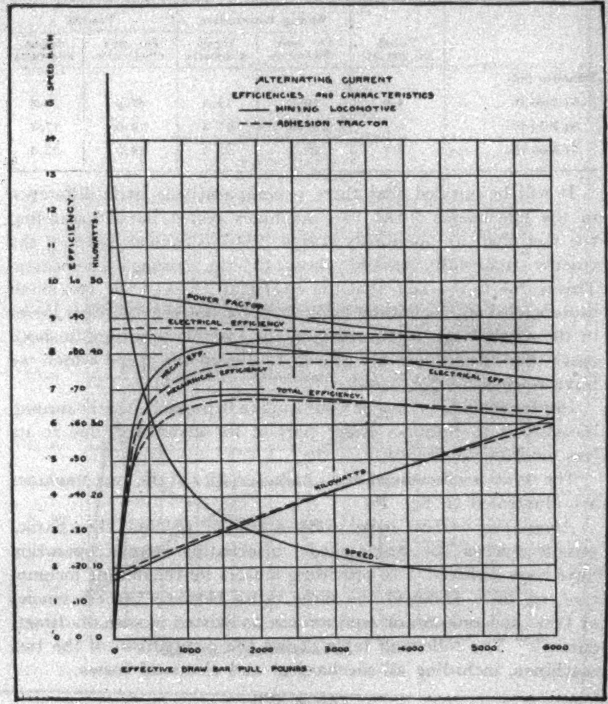


FIG. 20

In this case, as in the case of direct-current equipment, it is evident that the difference in efficiency of the mining locomotive and the tractor, and of alternating-current and direct-current equipment, are relatively unimportant as compared with other factors upon which the choice of one or the other as a system of electrical haulage must depend.

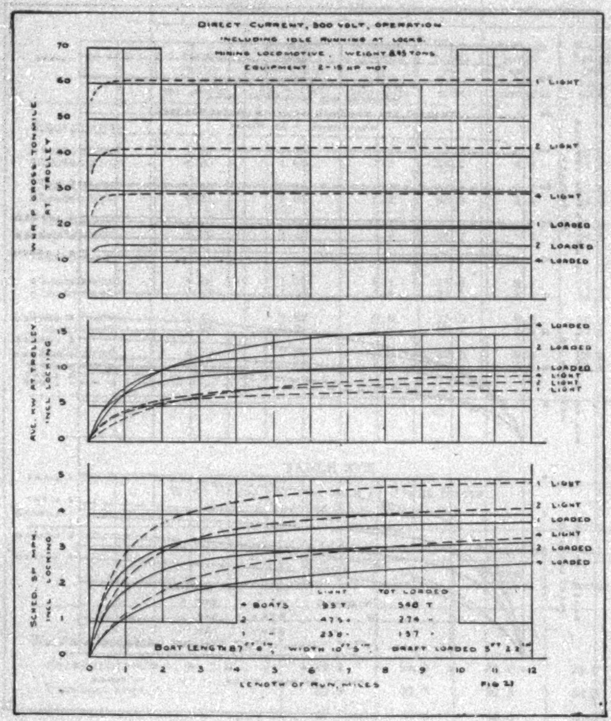


Fig. 21

Characteristic curves showing the average speed including locking for runs of different length, the average power required at the trolley, and the watt-hour per ton-mile for four-, two-, and one-boat tows for the mining locomotive and the tractor and for both alternating current and direct current are shown in Fig. 21, 22, 23, and 24.

The average length of run for the entire canal is 1.52 miles, and from calculations we have made it appears entirely practicable to use a run of this length as typical for the entire canal. Table XVIII shows the more important points brought out by these curves, on the basis that the locks are enlarged as necessary to accommodate two-boat tows.

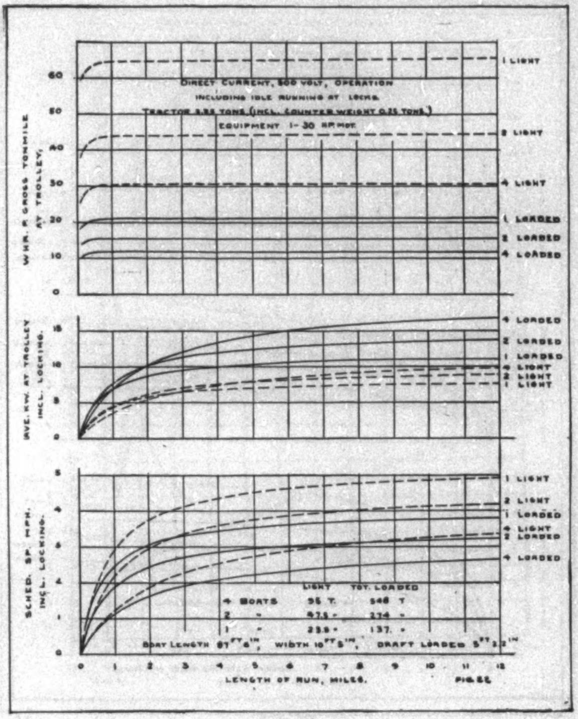


FIG. 22

## TABLE XVIII

SPEED, KILOWATT INPUT, AND WATT-HOURS PER TON-MILE. AVERAGE RUN 1.52 MILES —TWO-BOAT LOCKS. TIME LOCKING: 4 BOATS 35 MIN.; 2 BOATS 15 MIN., 1 BOAT 10 MIN.

| | Speed | | Mining Locomotive | | Tractor | |
|---|---|---|---|---|---|---|
| | Maximum speed mi. per hr. | Average speed including locking mi. per hr. | Average input at trolley kilowatts | Watt-hours per ton-mile | Average input at trolley kilowatts | Watt-hours per ton-mile |
| *Direct current.* | | | | | | |
| 4 boats loaded.... | 3.00 | 1.40 | 8.7 | 11.3 | 8.8 | 12.0 |
| 4 boats empty.... | 4.00 | 1.60 | 4.3 | 29.2 | 4.6 | 30.3 |
| 2 boats loaded.... | 3.45 | 2.22 | 9.1 | 14.8 | 9.3 | 15.5 |
| 2 boats empty.... | 4.57 | 2.65 | 5.2 | 41.9 | 5.4 | 44.0 |
| 1 boat loaded..... | 4.00 | 2.81 | 7.7 | 20.0 | 8.0 | 21.0 |
| 1 boat empty..... | 5.30 | 3.42 | 4.9 | 61.0 | 5.2 | 64.5 |
| *Alternating current* | | | | | | |
| 4 boats loaded.... | 2.88 | 1.37 | 8.1 | 11.0 | 8.2 | 11.1 |
| 4 boats empty.... | 4.13 | 1.59 | 5.0 | 33.5 | 5.3 | 34.8 |
| 2 boats loaded.... | 3.45 | 2.22 | 9.6 | 15.5 | 9.9 | 16.0 |
| 2 boats empty.... | 4.98 | 2.78 | 6.6 | 50.8 | 6.8 | 53.0 |
| 1 boat loaded..... | 4.19 | 2.90 | 9.0 | 22.6 | 9.4 | 23.3 |
| 1 boat empty..... | 6.00 | 3.67 | 6.7 | 77.0 | 6.9 | 80.8 |

## TABLE XIX

WATT HOURS PER TON MILE AT POWER HOUSE
(AVERAGE FREIGHT HAUL 55.6 MILES)

| Ton—2000 lb. | Direct Current | | Alternating Current | |
|---|---|---|---|---|
| | Mining locomotive | Tractor | Mining locomotive | Tractor |
| Watt-hours per total ton-mile | | | | |
| Four-boat tows.................. | 24.6 | 24.8 | 22.6 | 23.0 |
| Two-boat tows.................. | 30.9 | 32.5 | 32.5 | 33.8 |
| One-boat tows.................. | 42.8 | 45.3 | 48.3 | 50.2 |
| Watt-hours per freight ton-mile | | | | |
| Four-boat tows.................. | 33.9 | 37.2 | 32.5 | 33.1 |
| Two-boat tows.................. | 44.5 | 49.7 | 46.7 | 48.6 |
| One-boat tows.................. | 61.5 | 69.0 | 69.5 | 72.2 |

For the conditions existing on the Lehigh and Delaware Canals, it is estimated that the efficiency of a system of electric power transmission and conversion supplying direct current to motors will approximate 70 per cent. from bus-bars at power house to motor terminals. If alternating-current motors be used the calculated corresponding efficiency is 75 per cent. Based upon these efficiencies and the traffic conditions as existing on the Lehigh and Delaware canals, the watt-hours required

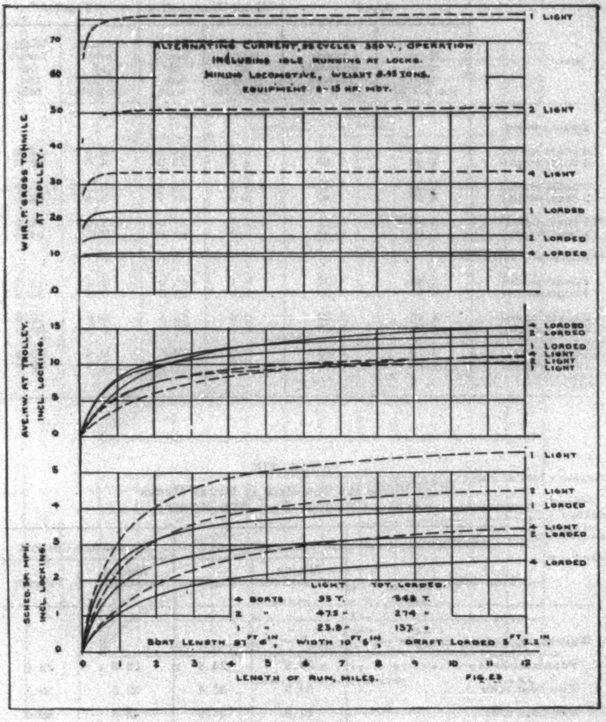


FIG. 28

at the power house per total ton-mile and per ton-mile of freight handled are given in Table XIX.

It should be noted that the calculated power for canal transportation, as set forth in the above table, applies only to the

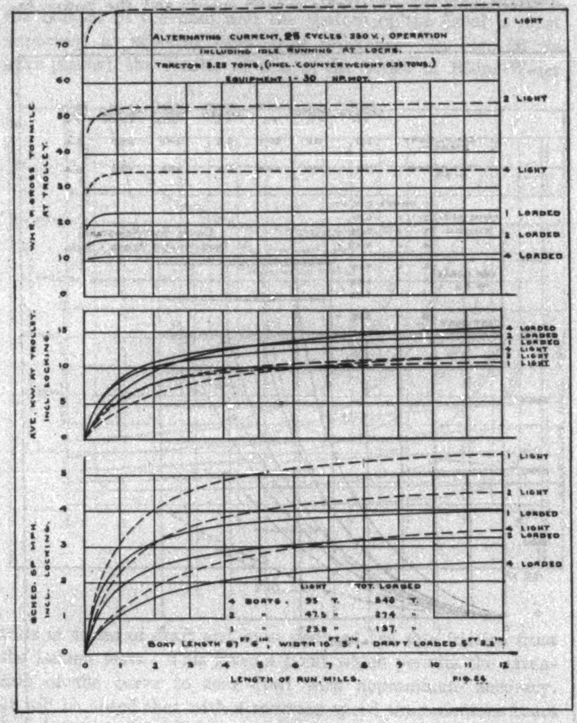
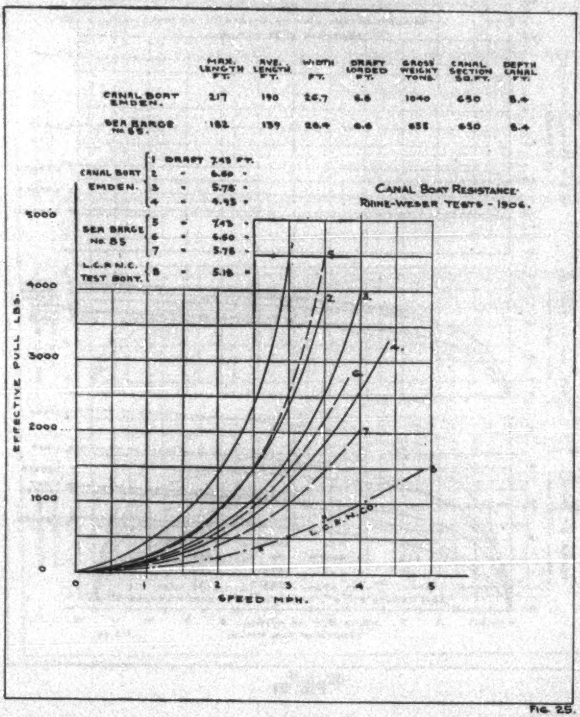


FIG. 24

especial conditions imposed by the physical limitations of these particular canals and by the speeds for loaded and for light boats which we have selected as most suitable for their operation.

## Appendix.

The tests conducted on the Lehigh Canal were for the purpose of determining the practicable towing speeds and the power required to pull a boat of the type used on that canal. A general investigation of canal-boat resistance was not attempted. It is



| | MAX. LENGTH FT. | AVE. LENGTH FT. | WIDTH FT. | DRAFT LOADED FT. | GROSS WEIGHT TONS. | CANAL SECTION SQ. FT. | DEPTH CANAL FT. |
|---|---|---|---|---|---|---|---|
| CANAL BOAT EMDEN. | 217 | 190 | 26.7 | 6.6 | 1040 | 650 | 8.4 |
| SEA BARGE No. 85. | 182 | 139 | 26.4 | 6.6 | 655 | 650 | 8.4 |

Fig. 25

of interest, however, to compare the results with those obtained in the very complete tests made by Sympher, Thiele, and Block on the Rhine-Weser Canal in 1906. In Fig. 25 we have reproduced the results of these tests, as well as the results obtained on the Lehigh Canal.

The Rhine-Weser curves indicate that the clearance between the bottom of the boat and the bottom of the canal is most important as affecting canal boat resistance. In Fig. 26 we have plotted the results of one of the series of Rhine-Weser tests in terms of draft and have deduced the skin friction from the Lehigh tests. This gives a point which permits the extension of the curve to zero draft with approximate accuracy. It will be noted that with a constant speed the resistance bears but slight relationship to the ratio of canal to boat cross-section, but is affected to a much greater extent by the clearance between the boat and the bottom of the canal.

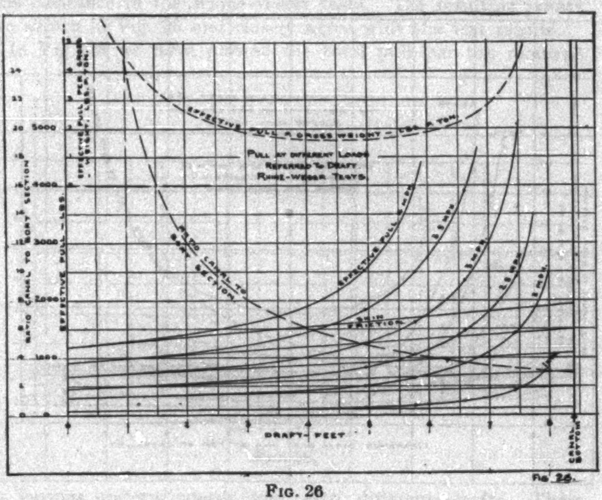


Fig. 26

In Fig. 27 we have plotted the difference between the total friction and the skin friction in terms of resistance per square foot of bottom surface as related to the clearance below the bottom of the boat. The points shown are from two tests, the boats in each case having the same cross section but different lengths and differently shaped bow and stern. The results show a fairly close agreement in the unit of resistance as referred to the bottom clearance. It is unfortunate that the tests did not include boats of the same draft but with different bottom clearances, but the data obtained indicates the importance of the clearance below the bottom of the boat, a point that until recently has been generally overlooked in canal work.

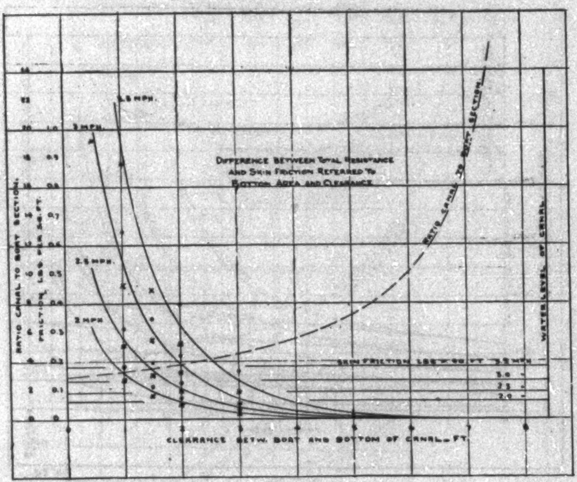


FIG. 27

An interesting point brought out by this method of plotting the test results is that the sea barge No. 85, with the same cross-section as the canal boat Emden, but with a length of 182 ft. instead of 217 ft., shows the smaller unit resistance as referred to the bottom clearance. The increase in unit resistance in case of the longer boat is probably due to the reduction in bottom clearance on account of the settling of the boat and the angle assumed by it relative to the general surface of the water under speed conditions. If the angle is the same in both cases, the stern of the longer boat will be brought closer to the bottom than will that of the shorter boat, with the result that the effective bottom clearance will be reduced. It will be noted that this effect is most marked at higher speeds, as we should expect to be the case.

As a matter of interest, the unit values in Fig. 27 have been applied to the boat as tested on the Lehigh Canal, the average bottom clearance being estimated at 1.57 feet, and the ratio of canal section 8 to 1 as compared with 3.6 to 1 as existed with this clearance in the Rhine-Weser tests. The resulting points are shown in Fig. 25 and closely agree with the test results.

In Fig. 28 we have plotted the total pull per ton required at various uniform speeds and with different drafts. These curves show that for a given speed there is a load at which the pull required per ton is a minimum, and that the pull required per ton increases rapidly as the clearance beneath the boat is diminished beyond a certain point. A relatively small clearance is permissible at low speeds but at the higher speeds which can be attained in mechanical towing the bottom clearance must be carefully considered.

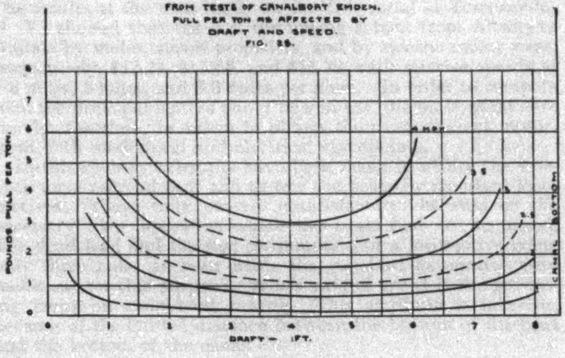


FIG. 28.

The important fact brought out by the curves plotted in Fig. 28, is that the power required to tow a canal boat at a given speed is a minimum per ton of gross weight when the draft is approximately one-half the depth of the canal. The curve of resistance at a given speed with different drafts closely approximates a hyperbola; and a hyperbola, representing the resistance, divided by a straight line, representing the tonnage as referred to draft, gives a minimum at one-half the depth of the canal. The same law probably applies to the width of the boat as compared with the width of the canal. With data of similar character and with known cost of power, crews, and canal-boat maintenance, the most economical type of boat and speed for a given canal can be determined.

## Discussion on "Notes on Electric Haulage of Canal Boats." New York, March 13, 1908.

**Richard Lamb:** This seems an opportune time to discuss this subject, for the public at large seems to be giving considerable attention to the subject of the waterways. The government officials at Washington are suggesting that there be legislative enactments in the matter of the water powers, so that these powers can be conserved for future use. Undoubtedly, in many cases these water powers will be used to propel boats, especially if such work as has been illustrated here to-night is carried to completion.

I do not agree that efficiency can, to a great extent, be disregarded. As engineer for the company that contracted to tow canal boats on the New York State canals, I had occasion to investigate, in a practical way, the subject of canal-boat towing. The results of the tests made on the Erie canal at Tonawanda, N. Y., showed that the cost for towing a boat from Albany to Buffalo by mules, steam propellers, and by electric motor were, respectively, $42.24, $17.60, and $15.32, with relative speeds of 1.3 miles, 3 miles, and 3.6 miles per hour. In order to compete with the principal motive power now in use, the mule, great care should, therefore, be taken to obtain the most efficient motor, from both mechanical and electrical standpoints.

In this country attempts have been made to utilize the towpath for a railroad bed, and to tow the boats by standard locomotives. These tests proved unsatisfactory, because of the necessary slow speed at which the boats had to be towed. The dead load and the fuel consumption of a locomotive going only three miles an hour made the standard locomotive very inefficient for this purpose. A low rate of speed is the governing factor in canal-boat towing. This attribute is inherent, because of the limited distance between the bottom of the boat and the bottom of the canal.

It sounds like a paradox to say that when a canal boat is pulled at its maximum speed, it stands still. The bottom of an Erie canal-boat is nearly flat and is 17.5 ft. wide. The distance from the bottom of a loaded boat to the bottom of the canal is one foot. Conceive of an area equal to the width of boat and the distance from the bottom of the boat to the bottom of the canal as being an orifice through which water must flow. The area is 17.5 sq. ft. When the boat is standing still there are 12,827 gallons of water under her. At 6 miles per hour, 1166 gallons per second would have to pass through 17.5 sq. ft. of sectional area, if the boat remained as it was; but as a matter of fact the boat settles as the speed increases, and therefore the sectional area under the boat decreases, making it impossible for so large a quantity of water to pass under the boat in so limited a time. Hence the water passes to easier channels, to both sides of the boat, until there is no water under the boat and it stops. Therefore, as soon as the maximum speed is reached, the boat stops.

An intumescence of the water at least one-foot high forms about a loaded Erie canal-boat when going three miles an hour. This water, not being able to pass under the boat, passes to either side, making a wave. At four miles an hour, a loaded canal boat on the Erie canal generates dead water under the stern so that it is practically impossible to steer her, and the curves on the canal make navigation at this speed difficult and dangerous. I consider that after equating for first cost and maintenance of canal and electric towing plant, and the maximum carrying capacity of boats, that a speed of three miles an hour is the greatest that should be sought. The wash of the canal bank, caused by the waves generated by a boat going more than three miles an hour is no inconsiderable factor in maintaining the canal.

In the paper under discussion all the records of the draw-bar pulls are referred to the components of the parallelogram of forces, the resultant of which would be the tow-line. I do not see the object of doing this. I think that a comparison of the actual tow-line pulls would be more satisfactory, especially as the angle made by the tow-line with reference to the course of the towing motor would vary but little.

The tests recorded, show that a tractor weighing 6493 lb., and getting its tractional friction from the pull on the tow line, is not so efficient as a mining electric locomotive weighing 16,000 lb. The tractor exercised a greater resistance to its own propulsion than a mining electric locomotive of over twice its weight. The experiments demonstrated that a " tractor must have a pressure made upon the wheels equal to the weight of a locomotive that will give similar traction ". It is evident that a tractor that gets its tractional friction independent of its weight, or independent of a friction that would impede its progress to the same extent as that of a locomotive of sufficient weight to give a similar traction, would be much more efficient than either of the types of motors tested. In designing the motors for the tests on the Erie canal, and the Finow canal in Germany, I succeeded in producing an efficient motor, working independently of its weight. The lighter it can be built, the more efficient it becomes. These motors are described and illustrated in the New York State Engineer's reports, also in the TRANSACTIONS of this Institute and those of the American Society of Civil Engineers.

The motor tested on the Finow canal in Germany weighed 1984 lb. It carried a 5-h.p. motor. It pulled the loaded boat with ease at the speed for which it was geared to run, namely, 2.5 miles per hour. The tow-line pull was 575 lb. The electric motor did not consume its full quota of watts. This was done on a cableway track. If a low I-beam track were used, the efficiency would have been greatly increased, as the motor would not have had grades to climb on approaching the supports. With such a track, this towing system would be ideal, especially if single-phase current were used for the electrical transmission.

**C. P. Steinmetz:** During the rapid expansion of our railway system, the canals had to take a rather secondary position, but it is gratifying to know that general interest in canals and in water transportation is reviving, and that the government is considering the improvement of the Mississippi waterway, and that the state of New York is rehabilitating the Erie canal.

What would be still more interesting than the paper is, not merely a comparative test of two rival systems, but a comprehensive paper covering the subject of canal haulage; that is, a comparison of the relative advantages, efficiencies, financial economies, etc., of the different systems of electric haulage, of steam propulsion, and of other methods, which have not been mentioned. Other methods are the chain drive, where a chain is laid at the bottom of the canal or river, and raised up to propel a boat, carried over a drum, and dropped again. I understand that this system gives good service abroad. And let us not overlook the *mule*. Mule propulsion of a canal boat appears to be a rather antiquated method, but we may find, nevertheless, that mule power, is, after all, under some conditions, the most economical form of drive. Comparing the cost of electric power per ton-mile as given in the paper with the cost of maintaining the same mule power, I should not be astonished to find that under the average conditions of canal haulage, the mule is the cheaper power. I am told that mules are cheap to buy and maintain, and are long-lived.

In systems of canal haulage a condition essentially different from that of the railroads has to be met, in that most of the canals are public highways; that is, any boat has a right on them just as a cart has on a public street. A railroad company has exclusive control of its right-of-way. Electric propulsion, then, must not interfere with mule or steam propulsion, or any other established method of propulsion on the state or national canals. Financially, the most serious feature is that canal traffic, in very many cases, is extremely light and intermittent. It exists only for part of the year, and the traffic varies considerably from year to year. Any equipment installed to take care of the maximum traffic would lie idle a part of the year, and might be very uneconomically used during some years. Under such conditions an electric system may be rather uneconomical. One of the chief advantages of the canals is the greater independence of the railroad which they confer.

It appears to me, therefore, that to show a superior efficiency to other forms of haulage, the field which electric haulage would cover, the traffic which it would take care of, would not be the traffic which exists now on waterways like the Erie canal, but a new form of traffic which would probably be created. The trolley lines have not taken the traffic of the steam railroads, but built up a new traffic; and I can well see that it might be possible to establish a profitable system of electric haulage on the numerous waterways of the country. A further careful investigation of the subject would be of considerable interest and of great benefit to the engineering profession.

**L. B. Stillwell:** The comparison of the two traction engines that we have made has resulted in certain determinations of comparative energy required and of actual energy required which have an application wider than we have attempted here to give them.

As regards efficiency of the contrasted machines, while the difference in favor of the locomotive is not controlling, it should not be minimized too far. Table 5 evidences clearly that from the mechanical standpoint the tractor is materially less efficient than the mining locomotive. While the difference in losses is small in comparison with the total energy utilized, it is large when expressed in terms of losses. For an effective pull of 2000 lb., for example, the mining locomotive loses an equivalent pull in the machine equivalent to 400 lb., while the best of the tractors loses 600 lb. The lesson to be drawn is that the tractor needs mechanical improvement.

With reference to Dr. Steinmetz' remarks in regard to a broader treatment of the subject than is attempted in this paper, I would say that in the course of the same investigation upon which our paper is based we studied the economy of the electric haulage system as compared with haulage by mules and established, to our own satisfaction at least, that if a canal is worked at anything approximating its full traffic capacity, electrification will pay handsomely.

In the case of the canals of the Lehigh Coal and Navigation Company, assuming some improvements in certain locks and an increase of traffic to a point approximating the full capacity of the canal, we estimated that the cost of operation, including all capital charges, could be reduced below one-half a cent a ton-mile. The grand average cost of freight transportation in the United States by railroads slightly exceeds 4 mills per ton-mile without any capital charges, locomotive repairs and renewals, being charged generally against cost of operation. It is safe to say, therefore, that if these canals were worked to their full capacity, even with the small barges now employed, the cost of transporting freight per ton-mile will closely approximate the average result attained in steam railroad practice to-day. With larger barges and larger locks, the cost of transportation would be further reduced; but everything depends, as Dr. Steinmetz suggests, upon the amount of traffic. The occasional mule is a proper engine when the traffic is very light, but if the traffic can be worked up to a reasonable extent it will pay to electrify. The capital costs when divided by a very large number of ton-miles per annum are reduced to so small an amount that they are absorbed by the general economies resulting from electrification.

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# CHARACTERISTICS OF MOTORS FOR LARGE SHEARS

BY BRENT WILEY

The function of a fly-wheel in a system with a rapidly fluctuating load is to equalize the power requirements, thus reducing the sudden shocks to the moving parts and thereby the strains on the machine frame and both the mechanical and electrical strains on the driving motor. For the fly-wheel to be effective the speed characteristic of the motor should be such that the motor will slow down as the load increases and will increase in speed as the load decreases. In the case of large shears the full working load is applied suddenly and the fly wheel is called upon to deliver energy through a very short space of time, varying from one-half a second to two seconds, according to the size of the machine and the size and condition of the material cut. Thus it is evident that the speed characteristics of the driving motor must be inherent, as the time is too short to depend upon a practical control means for changing the motor characteristics.

The ideal working condition for motor-driven shears would be one in which the fly-wheel does all of the cutting work, leaving for the motor only the friction load and the work of accelerating the fly-wheel after the cutting and subsequent slowing down period. The results of a test made on a large bloom shears, which is referred to later, show that this ideal condition can be approximated very closely when the speed characteristics of the motor are properly chosen.

Before outlining the exact conditions which the motor speed characteristics should meet, it would be well to analyze the speed curves of a shunt, a standard compound, a 50 per cent compound, and a series direct current motor. These curves as shown in Fig. 1 are designated by the letters *A*, *B*, *C* and *D*, respectively, and are given for a 50 h.p., 220-volt, direct-current motor.

For shears requiring a motor of 25 h.p., or of larger capacity, the friction load will approximate 25 per cent of the motor rating; for smaller shears the friction load varies from 15 per cent to 20 per cent of the full load.

The speed variation for a given change in load and the percentage of energy given up by the fly-wheel for the respective changes in speed are as follows:

*Curve A*.

| | |
|---|---|
| Shunt motor, speed variation from light to full load | 5 per cent. |
| The energy of a fly-wheel varies as the square of the speed and the amount given up for 5 per cent speed variation is | 10 per cent. |

*Curve B*.

| | |
|---|---|
| Standard compound motor, speed variation from light load to full load | 15 per cent. |
| Standard compound motor, speed variation from friction or 25 per cent load to full load | 10 per cent. |
| Energy given up by fly-wheel for 10 per cent speed variation | 19 per cent. |

*Curve C*.

| | |
|---|---|
| 50 per cent compound motor, speed variation from light to full load | 50 per cent. |
| 50 per cent compound motor, speed variation from friction or 25 per cent load to full load | 30 per cent. |
| Energy given up by fly-wheel for 30 per cent speed variation | 51 per cent. |

*Curve D*.

| | |
|---|---|
| Series motor, speed variation from 25 per cent load to full load | 66 per cent. |
| Speed at 25 per cent load | 1500 rev. per min. |
| Speed at full load | 525 rev. per min. |

With but few exceptions the electric motor drive is now used in all machine shops, and the replacing of worn-out engines with motors for individual and group drive is completing this evolution. Where such a change is to be considered in regard to engine-driven shears, it is comparatively a simple matter for an engineer to determine the size of the motor and the proper speed characteristics to give the best results. For example, in the case of a large hot bloom shear

| | |
|---|---|
| The fly-wheel capacity of the machine | *A* h.p. seconds. |
| Friction load of machine | *B* amperes. |
| (obtained by test) | (at a given voltage) |
| Cutting period | 2 seconds. |
| Period between cuts | 6 seconds. |

(This cycle is to be considered continuous.)

If the power is cut off when the machine is running light at full speed, the number of consecutive cuts that can be made before the machine comes to rest is four. For the ideal case, where the fly-wheel does all of the work, it should give up 25 per cent of its energy per cut and must slow down 13 per cent.

Let the light load of the motor = *C* rev. per min.

During the cutting period the speed must fall to *C* rev. per min. 100 per cent − 13 per cent = 87 per cent *C* rev. per min.

Energy delivered by the fly-wheel during two seconds' cutting period and energy stored in the fly-wheel during the six seconds interval = 25 per cent *A* h.p. seconds.

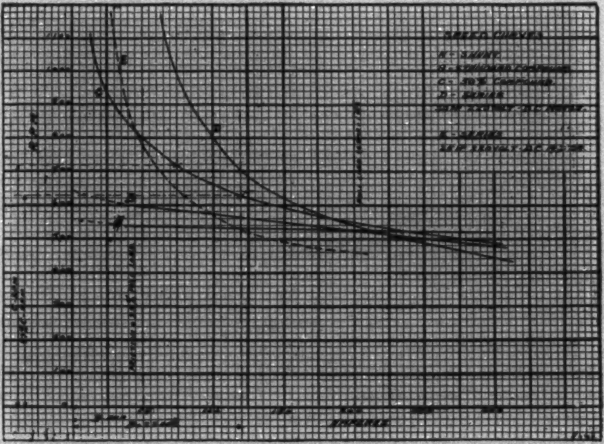

FIG. 1

Let the average current required to store 25 per cent *A* h.p. seconds energy in the 6 seconds interval = *D* amperes.

The current curve which corresponds to the power curve with constant voltage will vary through an economical range when the motor speed-characteristic governs the variation as follows:

The minimum value of the current should be equal to a friction load at the end of the interval between the cuts. The maximum value of the current should be equal to the friction load plus twice the value of the average current required to store the fly-wheel energy expended during one cut. The curve in Fig. 2 illustrates this.

During the cutting period the current rises to a maximum value as shown at point *X*, and falls to a frictional load value as shown at *Y* at the end of the 6-sec. interval. Thus, at the point *Y*, *B* amperes corresponds to *C* rev. per min., and establishes one point on the motor speed curve. This shows that it

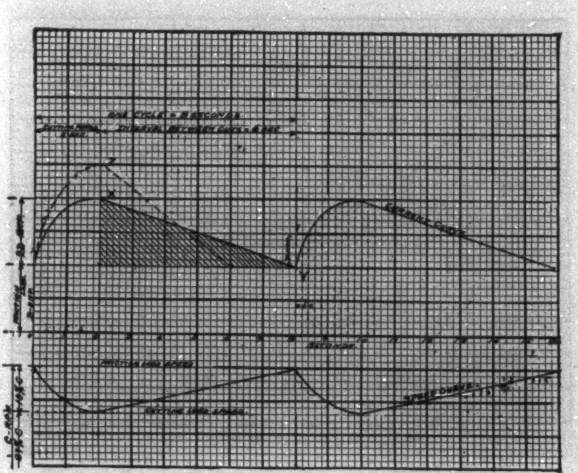

FIG. 2

requires *D* amperes as an average to store the 25 per cent *A* h.p. seconds energy in the fly-wheel. Thus the maximum value of the current at point *X* equals 2 *D* amperes, which must correspond to 87 per cent *C* rev. per min., and a second point on the motor curve is established. By this means a speed curve for the working range required can be plotted. As an illustration, these points are designated on curve *C*, Fig. 1.

The heating effect of the motor load varies as the square of the current and is represented by the square root of the mean square current. This value of current can be closely approximated by dividing the current curve into a number of parts along the time ordinate, squaring each sectional current value and multiplying by the time-increment. These several values are then added and the sum divided by the total time period. The square root of this dividend is the square root of the mean square current. For example, refer to Fig. 2.

Square root mean square current

$$=\sqrt{\frac{(a^2 \times 0.2)+(b^2 \times 0.2)+(c^2 \times 0.2) \text{ etc.}}{8}}$$

and this is the value of a continuous current which would produce the same heating effect as the varying load shown. The capacity of the motor required for the above condition can thus be calculated.

With the principal portion of the speed curve constructed and the capacity of the motor known, the next point for consideration is the type of motor winding and consequently the speed characteristic which is best suited for the given conditions.

As has been explained before, the speed variation of a series motor covers too great a range between the friction load, or 25 per cent full load, and the working of full load of the motor. This value is approximately 66 per cent, and therefore the series motor can be eliminated from the list.

The next motor to be considered is one with a 50 per cent compound winding, in which case the full-load speed is 50 per cent of the light-load speed.

Fig. 3 is a recorded current curve of a 50 per cent compound motor operating a large bloom shears which has the following characteristics:

| | |
|---|---|
| Style of machine | Vertical, bloom. |
| Maximum section the machine will cut | 10 in. by 10 in. |
| Weight of fly-wheel | 20,000 lb. |
| Diameter of fly-wheel | 9 ft. 10.5 in. |
| Section of fly-wheel rim | 12 in. by 13 in. |
| Rev. per min. of fly-wheel | 110 |
| Energy of fly-wheel at friction load | 2500 h.p. for 1 sec. |
| Size of motor | 50 h.p., intermittent rating. |
| Voltage of motor | 220 |
| Type of motor winding | 50 per cent compound. |
| Motor | direct-current, geared |
| Motor speed | 500 rev. per min. full load. |
| Friction load | 50 amperes, 235 volts, 800 rev. per min. |
| Cutting load, maximum | 110 amperes, 235 volts. |

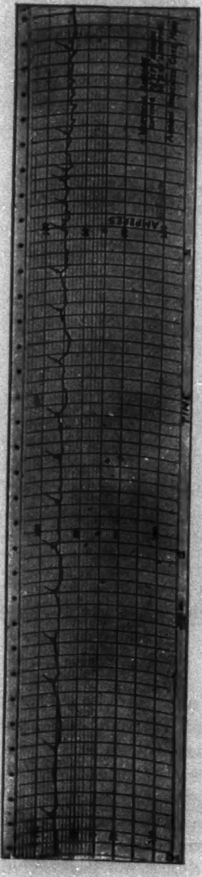

FIG. 3

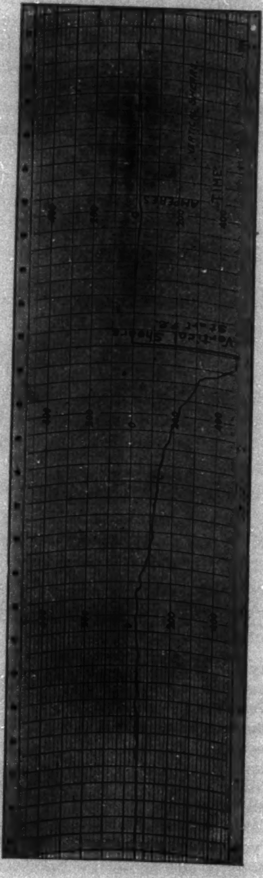

FIG. 4

Section of material cut......................7.5 in. by 7.5 in.
Kind of material cut..............................hot steel

When the machine is running light at full speed and the power is cut off the number of consecutive cuts that can be made before machine comes to rest is four.

Motors used for intermittent duty, such as street car and crane service, are given an intermittent rating and will operate at full load for one hour without injurious heating; this heating is generally stated as 75 degrees cent. rise above the surrounding atmosphere. The above motor is rated on this basis, and the continuous load which it will carry with the same temperature rise is equal to practically one-half of the 1-hr. rating.

As shown on the curve, the motor is working between an average minimum load of 95 amperes and a maximum of 110 amperes. Estimating on the square root of the mean square basis, the equivalent heating current is approximately 100 amperes at 225 volts; this requires a 25-h.p. motor, continuous rating, or a 50-h.p. motor of intermittent rating.

The starting conditions as shown in Fig. 4 require a maximum of 100 h.p. which falls gradually to the friction load of 125 h.p. in 40 sec.

The curve in Fig. 3 shows virtually a uniform load on the motor, a much greater load than that given for the theoretical case in Fig. 1. An analysis of the condition shows, however, that the motor is working in a very steep portion of its speed curve; and the speed change for this working portion of the 50 h.p., 50 per cent compound-wound motor of intermittent rating is equal to 75 per cent of the speed change of a 25 h.p. series motor of continuous rating.

50 per cent compound motor 95 ampere 670 rev. per min.
" " " " 110 " 640 rev. per min.
Reduction in speed.................. 30 rev. per min. = 4.5 per cent.
Series motor.............. 95 ampere 580
" " ..............110 ampere 545
Reduction in speed.................. 35 rev. per min. = 6.0 per cent.

The steeper the speed curve the more gradual is the fall of the current curve from the peak to the minimum value. Referring to the theoretical curve in Fig. 2, a motor with a certain percentage of compounding will require a maximum current, as designated at point *X*, to give the required speed change of 13 per cent; a motor with less compounding will require a maximum current rising to point *Z* for the same speed reduction. The shaded portion of the curve from point $X$ to point $Y$ represents the work done in restoring energy to the fly-wheel. It is obvious that an increase in the peak load or vertical component causes a corresponding decrease in the horizontal or time ordinate, as the area described by the curve beyond the peak remains constant. Therefore the steeper the motor speed-curve the more gradual the decrease of current value between the cutting periods. On account of this sluggish characteristic, it requires quite an appreciable time, virtually 14 seconds, Fig. 4, for the motor described above to increase the speed of the fly-wheel from the speed corresponding to 110 amperes to that corresponding to 50 amperes, or friction load. As a cut is made in about every 9 sec. the minimum value of the current does not reach the friction load. This is the principal reason why the obtained load curve is so much smoother than the theoretical curve of Fig. 2.

For the particular application given above, the 50 per cent compound motor proves to be a fairly good series motor regarding speed characteristics; it requires only a slight increase in load to give the speed reduction required by the fly-wheel in order that it may do the greater portion of the work. Compared with its continuous electrical capacity, this type of motor has great mechanical strength, and it is capable of standing heavy overloads for a short period of time. Thus it is apparent that both mechanically and electrically this motor has better characteristics than the motor of continuous rating for a heavier kind of work.

The curve of Fig. 5 shows the working load of a hot bloom shears driven by a direct-current, 220-volt motor of 25 per cent compounding. The general characteristics of the machine and motor are as follows:

| | |
|---|---|
| Style of machine | horizontal bloom. |
| Maximum section the machine will cut | 10 in. by 10 in. |
| Length of blade travel | 15 in. |
| Rev. per min. of cam or crank-shaft operating blade | 17 at 850 rev. per min. of motor. |
| Weight of fly-wheel | 12,700 lb. |
| Diameter of fly-wheel | 8 ft. |
| Section of fly-wheel rim | 10 in. by 12 in. |
| Rev. per min. of fly-wheel at friction load | 350 |
| Energy of fly-wheel at 350 rev. per min. | 5900 h.p. for 1 sec. |
| Size of motor | 125 h.p. |
| Type of winding | 25 per cent compound. |
| Motor | direct-current, geared. |

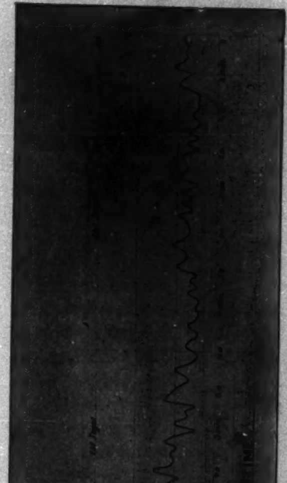

FIG 5

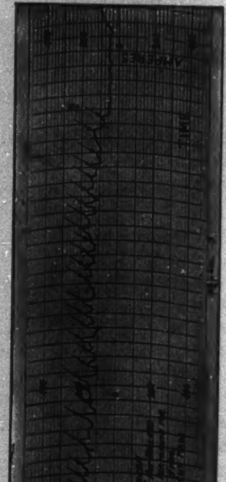

FIG 7

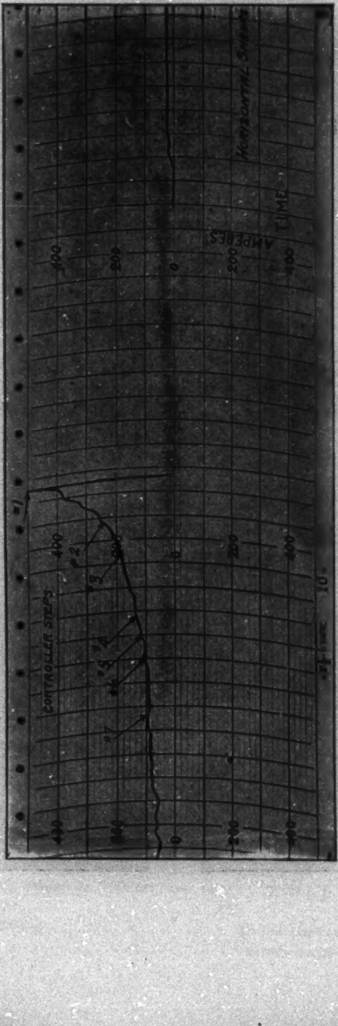
HORIZONTAL SHEAR
TIME
AMPERES
400
200
0
200
400
CONTROLLER STEPS
#1
#2
#3
#4
#5
#6
#7
10

FIG. 6

| | |
|---|---|
| Motor speed | 660 rev. per min. full load. |
| Friction load | 100 amperes at 225 volts, 850 rev. per min. |
| Cutting load | 200 amperes, at 225 volts. |
| Section of material cut | 8.5 in. by 7.25 in. |
| Kind of material cut | hot steel. |

When the machine is running at full speed and the power is shut off, the number of consecutive cuts that can be made before machine comes to rest is four.

The curve was plotted from readings taken at 3-sec. intervals The current reaches a maximum value of 300 amperes and is much more fluctuating than that indicated by the curve of Fig. 3, although the fly-wheel effect is more than double. With a motor of increased compounding the load fluctuation could be materially decreased.

The current would have excessive peak values with either a standard compound or shunt motor, although it has been found in some cases that for the same work done the heating effect on the standard compound motor was 25 per cent less than that on a shunt motor.

Increasing the fly-wheel capacity of the system has the same effect on the load curve as increasing the compounding of the motor, and it will consequently tend to flatten the load curve. If the fly-wheel capacity is decreased the load becomes very fluctuating, which is the same as decreasing the compounding of the motor, giving it a flatter speed curve. Fig. 6 shows the starting current and Fig. 7 the running current of a hot bloom shear driven by a motor of standard, or 15 per cent, compounding. If the fly-wheel capacity of this machine or the compounding of the motor were increased, a flatter current curve would be obtained.

Horizontal billet.

| | |
|---|---|
| Maximum section the machine will cut | 5 in. by 5 in. |
| Rev. per min. of cam or crank operating blade | 28 |
| Weight of fly-wheel | 3000 lb. |
| Diameter of fly-wheel | 5 ft. 6 in. |
| Section of fly-wheel rim | 14 in. by 3 in. |
| Rev. per min. of fly-wheel | 190 |
| Size of fly-wheel | 60 h.p. |
| Voltage of motor | 220 |
| Type of winding | standard compound. |
| Motor | direct current, belted. |
| Speed of motor | 640 full load. |
| Cutting load | 45 amperes at 230 volts. |

Section of material cut........................4 in. by 4 in.
Kind of material cut............................hot steel.

When the machine is running light at full speed and the power is cut off, the number of consecutive cuts that can be made before machine comes to rest is three.

## ALTERNATING-CURRENT MOTORS FOR SHEARS

The motors considered are designed for either 25-cycle or 60-cycle, three-phase circuits and are of the induction type. When it is necessary to start a fly-wheel type machine frequently, the motor should have a wound rotor provided with slip rings and external resistance for control. This type of motor gives very good starting conditions, as full-load torque is obtained at approximately 1.25 times full-load current as compared with 3 to 3.5 times full-load current for full-load torque with a squirrel-cage rotor.

Shears are usually operated continuously, so the starting current required is not of particular importance. It is desirable to have a motor of simple construction for continuous duty, and although some sacrifice is necessary regarding starting conditions, an induction motor with a cage secondary should generally be used for operating shears. The motor should be provided with high-resistance end-rings, as this form of construction gives very good starting conditions. As a maximum a 50 per cent increase in torque with a 30 per cent decrease in current and a 6 per cent decrease in efficiency at full load may be obtained. A second advantage in using high-resistance rings is that the motor has a speed characteristic very similar to that of a direct-current compound-wound motor, thus allowing the fly-wheel to be effective during the cutting period.

The amount of resistance that can be included in the end-rings without undue heating is limited, as this heat energy must be dissipated in the motor. Where the motor operates continuously under virtually full load the maximum slip that can be obtained with high-resistance rings is approximately 10 per cent; but for intermittent service the slip can be increased to 15 per cent without undue heating. The efficiency and power curves of the motor will be similar to those of a standard direct-current shunt-wound motor having sufficient resistance in its armature circuit to give 15 per cent drop in speed from light to full load; in other words, the slip of the motor varies according to the resistance in the end-rings. As the fly-wheel effect obtained from the system varies as the square of the speed at the high and low points during the cutting period, a slight increase in the resistance will produce a material reduction of the maximum load on the motor.

In shearing plates, the load is applied gradually and a motor with 15 per cent slip will have a fairly smooth load curve, the fly-wheel being of liberal proportions. In the cases of hot bloom and scrap shears, where the section to be cut is quite large and practically square, the nature of the work becomes more severe. The actual cutting period is short and the power required large, which makes it necessary to include large fly-wheel capacity; and in order to prevent excessive loads motor should have a steep speed-curve. In the case of direct-current work it has been shown that increasing the compounding of the motor to 50 per cent has materially improved conditions, giving in the case shown almost a uniform load curve. For induction motors, however, 15 per cent slip is a practical limit, therefore to reduce the peak load for the heavier classes of machines fly-wheel capacity must be added.

In any class of machines where the load is intermittent, especially when cast tooth gears are used in the reduction, the driving motor will be subject to considerable vibration. In many cases it is necessary to mount the motor on a frame or bracket support, although it is difficult to provide sufficient rigidity with this construction. This vibration causes undue wearing of the motor-bearings and tends to deteriorate the rotor-windings. The most effective way to prevent this vibration where gearing is to be used is to mount flexible coupling between the rotor and the driving pinion, which is keyed to a short length of shaft supported by two bearings. This form of construction has been adopted for a number of different drives where the work is very severe. It gives excellent results with little wear of the coupling parts and shows a decided decrease in motor maintenance.

The starting conditions are rather severe when the machine has large fly-wheel capacity and for shears as described above. The motor-starting apparatus should be of liberal capacity and should be provided with protective means to insure a gradual starting of the motor, thus preventing excessive starting currents. An autostarter is used for this work.

The starter consists of a double-throw, oil-immersed switch with the autotransformers mounted in the same case. Several extra taps are provided so that the most suitable starting condition can be obtained. In starting, the handle of the autostarter is first thrown to the right which closes the switch on the starting side. A lock is provided to prevent the handle from being thrown in the wrong direction, and unless held in position by hand on the starting side it will return automatically to the off position. After the motor has attained a nearly constant speed the handle is thrown quickly to the left and is locked automatically.

Fuses or a circuit-breaker may be employed to protect the motor against overloads while running, and these can be so connected that the starting current may exceed the running current without blowing the fuse or tripping the circuit-breaker.

Where there are a number of motors to be started, as in a steel mill, it is a practical arrangement to provide a single transformer centrally located for each group of motors. The transformers should be supplied with an extra tap to give approximately 65 per cent line voltage; for three-phase motors five line wires would be required for the motor feeder circuit. Thus instead of a number of individual transformers, one transformer of large capacity is used and the starting apparatus is limited to a double-throw switch.

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# THE ENGINEER'S ACTIVITY IN PUBLIC AFFAIRS—PUBLIC UTILITY COMMISSIONS AND FRANCHISE VALUATIONS

BY HENRY FLOY

Americans are, in a mild way, extremists. They start for the goal with such impetuosity and zeal that they often overrun the mark and then have to return to it. This is what is now happening to public opinion with reference to the corporations. No language is strong enough to express the public condemnation of corporate mismanagement, usurpation of power, and larceny of funds, which have recently been committed. On the other hand, all public utility corporations are not bad; and the engineer, knowing this, should be among the first to oppose the illogical, unreasonable condemnation of our present commercial system which causes a loss of the confidence on which our business relations are founded, and results in weakening the foundations of our whole economic structure.

As President Woodrow Wilson has truly said:

> Scathing indictments of our present industrial and political conditions are what we are suffering from at the present moment and they are to be offset, not by other scathing indictments, but by a very calm and self-possessed examination of actual conditions of things. What we need at present is not heat but light.

As a matter of fact, public sentiment is now undergoing a reaction; the American sense of right and fair-play is winning. The pendulum has reached its extreme position and is starting to swing back. The excesses in which the public mind has been indulging, indicated by the cry for indiscriminate municipal ownership, governmental and socialistic rule, are being replaced by a more sane demand for control and regulation.

It is beginning to be recognized that a corporation must not only serve the public but also the stockholders; that the public cannot be served by corporations unless the stockholders receive a return on their investment concomitant with the risk; that capital cannot be compelled to invest on terms unacceptable to it. This change of sentiment, however, does not mean, as is clearly evident to the well-informed engineer, that the public will ever again return to its former *laissez faire* policy toward corporations.

Just at this time, during this important readjustment of relations between the public and the corporations, it is proper, yes necessary, that the engineer should pause to consider the lessons to be learned from recent experience, formulate his opinions for the future, and thus be the better prepared to coöperate in ending the present feeling of unrest and antagonism and share in the successes of the new advance which is sure to begin soon. Although by education, training and experience the engineer is presumably well-balanced and not excitable, he may nevertheless be influenced by popular sentiment or the demands of the corporations or financiers. During this transition stage especially, when the demands upon his time are restricted, he should take the opportunity to verify his opinions, reestablish his conclusions, and calmly determine his future line of action.

With these thoughts in mind, this paper has been prepared to serve as an introduction to a discussion which it is hoped will help to a crystallization and unification of the ideas of the members of the Institute on but three, of many similar important nontechnical questions now demanding the serious consideration of broad-gauge engineers; namely, activity of engineers in public affairs, public utility commissions, and franchise valuations. The author's comments must not be taken as an attempt wholly to cover the subjects touched upon, or to reach conclusions which may not require modification, as the questions considered could very properly occupy the attention of the Institute at more than one session and they present viewpoints almost as diverse as is its membership.

*Activity of Engineers.* Considering the importance of the real work done by the engineer in the recent commercial development of this country, the comparatively unimportant public part taken by him is rather striking. His inconspicuousness can probably be accounted for by

(a) His keen interest in the purely scientific aspect of the enterprises with which he is connected; with him a " blunder is a crime ". The engineer, like the teacher or the ecclesiastic, has a certain love for his profession which absorbs and recompenses him, in a degree, independently of monetary reward or fame.

(b) His natural hesitancy in pressing his own claims to recognition. Most lawyers or politicians are ready speakers, used to argument, and therefore, by profession trained to make their own case a strong one.

(c) His lack, in the past, of a broad, general education, especially along the lines of history, political economy, and what Dr. Humphreys of Stevens Institute, in a recent address, called " business engineering ". A narrow, purely technical training does not conduce to a broad, liberal consideration of any subject.

(d) His too frequent inability to speak fluently in public. The engineer does much of his work individually, quietly, on paper, so that he often becomes embarrassed when called to express his opinion from the platform.

As a result of these limitations the engineer has hardly received the public recognition which would be expected. Perhaps the most striking recent illustration of this was in the appointments made to the two Public Utilities Commissions of the State of New York, which included fourteen high-class, well-paid officials. Of this number only one has had a technical training, although in the hands of these commissioners are placed, with almost despotic power, the affairs of large engineering enterprises in the State of New York, estimated to be valued at about $3,500,000,000. This exception is the more noticeable when it is considered that the same governor, in naming the Hepburn Commission to inquire into and report with recommendations as to the condition of banks, financial affairs, and their improvement, selected bankers; and, when a commission was named to consider and make recommendations with regard to the Torrens system of registration of land titles, the commission was almost entirely made up of men prominent in real estate matters. Mr. George W. Perkins, in a recent address, referring to a commission to have national supervision of railroads, said:

> It should be in the hands of experts. A railroad commission, for instance, should be composed of railroad men who can deal with the questions arising in a practical way. This kind of expert, high-minded super-

> vision would not be opposed by the business interests of the country. What they dread is unintelligent, inexperienced administration.

Mr. Perkins but expresses the accepted opinion that experts are the proper parties to have supervision of matters in which they are specialists. Even the New York State Court of Appeals, in a recent decision relating to the constitutionality of the statute creating a commission to determine rates, says :

> That the most appropriate method (speaking from a practical, not necessarily constitutional point of view) is the creation of a commission or body of experts to determine the particular rates has been said several times in the opinions rendered by the Supreme Court of the United States in the various railroad commission cases and in those of State courts.

It is well known that the House of Lords in England, when it sits as a Court of Appeals, has the cases submitted to its law members, which would seem to be the only rational practice. Contrary to such general belief, the opinion prevailing in selecting the New York State commissioners, as indicated by their appointment, was that if they possessed unquestioned integrity there existed no special reason for naming men experienced in handling engineering or transportation questions. This has resulted in the necessity of hiring engineering subordinates, which increases expenses and decreases direct responsibility, because the advice of more or less independent experts reporting on matters of detail is quite different in value from the advice given by a technical member of a board identified with its policy and responsible to the public for the discharge of his obligations. Hired experts can never be made to shoulder the responsibility for a decision rendered by a commission composed wholly of men untrained in public utility affairs and perhaps unable fully to appreciate the technical effect of their orders.

It is noteworthy that much of the work of the commissions is divided, one member investigating one question and a different member another. With two or three commissioners as engineers, the engineering questions would naturally devolve upon these members, and they could solve them much more quickly and unequivocally than could politicians, lawyers, or business men unacquainted with even the terms involved, to say nothing of understanding the practical conditions under which a lighting corporation, or steam or electric railway company, must operate. A perusal of the minutes of the hearings held before state commissions will convince any unprejudiced person that a disproportionately large amount of evidence and testimony is submitted, with consequent unnecessary financial expense and consumption of time for the purpose of explaining terms, apparatus, and methods of operation and expenditure to commissioners who, in general, should be acquainted with the matters being considered. This and similar evidence surely indicates that the efficiency of the commissions is largely reduced by lack of proper make-up. For this condition of affairs the engineers themselves are partly to blame.

The antiquated notion that every engineering expert is unable to appreciate any question outside of its purely technical significance is disproved by the fact that the success of the engineer is often based on a liberal education with wide experience, giving him a capacity for proper consideration not only of technical but also of commercial and political factors that enter engineering undertakings, and also by the fact that the administrative and executive staffs of many of our largest and most progressive organizations are being constantly recruited from the engineering profession. To become president of the Pennsylvania Railroad, judging from precedent, one must have, in addition to other qualifications, both a technical education and practical experience in engineering work.

By reason of the work and position of the engineer in the business and technical world, is it not reasonable to expect that at least one-half of the membership of the public utility commissions, being named from time to time throughout the country, should be composed of experienced, broad-gauge engineers. I venture to prophesy that as public service commissions become more common, they will be constituted more and more of men drawn from the ranks of those having practical experience with the work to be undertaken. In fact, I can conceive of no more independent, dignified, influential or beneficent occupation in which an engineer can be engaged, and I believe the honor of the position will ultimately attract to it our most capable men whom now the monetary inducement will not interest. The present inertness of the profession in these matters is noticeable. Last spring the writer personally sought to have the officials of some of our engineering clubs and societies develop sentiment looking to action on the part of these respective organizations toward obtaining the appointment of some men of engineering experience on the New York State commissions, but only one organization acted. The public utility corporations themselves, represented by a number of executive officers in conference, showed some interest in securing commissions capably constituted, but no definite results came from the conference. Even the labor unions have actively urged they be represented on the commissions, simply on grounds of self-interest, while the engineer, with especial qualifications for the work, has too much pride to ask recognition, even with semi-altruistic motives. It is a hopeful sign that for the first time in its history the American Society of Civil Engineers recently memoralized Congress, urging legislation for the preservation of our forests, a precedent which might well be followed by the Institute.

The importance of the engineer in commercial transactions is steadily growing, and he should recognize the claims upon him to take part in public affairs and assume the responsibility more and more laid upon him, of leadership. His increasingly closer business relations with public matters and his reputation for integrity give his opinion and influence steadily greater weight in large affairs, which he should appreciate, accept, and respond to. While the engineer's work must always be professional, in a way judicial, and should always be accompanied by high moral sense, the successful engineer must nevertheless combine practical business qualifications with his scientific work. There can be no good engineer—in a broad sense—unless combined with his technical conclusions there is included such recognition of commercial conditions, as will thereby permit him to attain the worthy objects of his chosen profession with maximum efficiency.

*Public utility commissions.* The aggressive, almost insolent, and oftimes unfair attitude of some utility corporations has created an insistent demand for further and more direct control of operations than has been possible through the more usual form of legislative enactments. The American people are not, as a rule, over inquisitive as to somebody else's business, but when imposed upon, they do not hesitate to ascertain the why and wherefore. The result has been a publicity of corporation finances and affairs that now implies an obligation to afford the corporations legitimate protection in their business.

The necessity for regulation by the public arises, in the first place, because the exercise of franchise rights by certain corporations, while academically not exclusive, is nevertheless practically non-competitive; therefore, one of the ordinary checks arising through competition does not in such cases apply. Unlike the individual or ordinary business corporation, a public utilities corporation frequently cannot begin business without being organized under special and specific laws. Such corporations may be granted unusual franchises; for example, the right of eminent domain, and are recognized as existing for service to the public in a manner, and with privileges entirely unique and distinct from those of ordinary business undertakings, and are therefore acknowledgedly subject to special regulation and control. Even ordinary business corporations which have no special privileges granted, if uncontrolled, may, as the result of unusual commercial acumen linked with a large aggregation of capital—illustrated for example, in the case of the so-called " trusts "—create a wrong which organized society will very properly step in and limit, control, or prohibit. Business trusts are in effect monopolies, because competition as a practical matter is out of the question, and hence regulation in their cases is also essentially necessary. The underlying principle of monopolies, coöperation, is a legitimate product of our present civilization; it may be controlled but not prohibited.

In the second place, regulation of utility corporations competing for the same business is required from the very nature of the business itself. If they are allowed to compete fully and freely, experience indicates that they will ultimately engage in a war of annihilation, the expense of which is in the end borne by the security holder or the public. Up to a few years ago, political economists believed and argued that the only regulation required for all commercial operations was free and unrestricted competition:

> Because the experience of mankind had not developed essential monopolies, and it was believed that every problem which would arise would be solved by giving full play to the spirit of competition. * * *
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> Whether that system of dealing with railroad corporations will succeed or not can be ascertained by viewing their history in the State of New York, and the experience which was had in this State, demonstrated that it did not work to the advantage of the public and that the evils connected with the system were simply enormous and unendurable. Competition could not exist upon railroads.*

Some years ago the state of Massachusetts appointed a Committee of Gas and Electricity empowered to inquire into and revise rates charged, operating costs, capitalization, and to limit competition. Although this commission was looked upon as something of an experiment, the high quality of work accomplished by it has commanded the respect and approval not only of the public at large, but also of the corporations themselves which, through its protection, have been guarded against unfair and unnecessary competition.

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* F. W. Stevens address, A. I. E. E. dinner, 1908.

Encouraged by the good work accomplished through this commission, and other commissions having to do with railroads, etc., and supported by those who were opposed to municipal ownership but believed that the conduct of corporations should be regulated and controlled, there has developed within the last year or two a popular demand for other state commissions with large powers that could compel, particularly railroads and gas and electric corporations, to comply with their obligations and furnish reasonable service at fair prices. Without attempting to discuss whether regulation should properly be undertaken by the state or federal government, it would appear that if intelligent regulation of such corporations as railroads is to be obtained, it must be done at least in part by the nation rather than through each state attempting to pass its own laws, perhaps contradictory to those of an adjoining state in which the same railroad must operate. On the other hand, state or even municipal control of gas and electric corporations might seem both logical and legitimate, provided the personnel of the board of control is capable, honest and unprejudiced. In fact, the corporations themselves, as a rule, welcome such regulation, as it will protect their properties from hostile and wasteful attacks, vicious competition, and unfair manipulation of its securities. Their objections are almost always based on either a fear of corrupt or dread of well-meaning, incompetent, and inexperienced men, as commissioners, or else that questions under consideration would be decided from the standpoint of the past rather than the present. For example, it would, of course, be unfair, to take advantage of the present investment of a corporation, of which the stockholders cannot unburden themselves, to make an unduly low price for its commodity. In each case the rate of return allowed a going corporation should be the same as that to a new corporation rendering the same service.

New York started in a mild way with several commissions for different purposes; but last year, under the leadership of Governor Hughes, the legislature passed laws substituting for the other commissions, two state commissions, one to have charge of all public utility corporations in Greater New York, and the other in the remainder of the state. To these two commissions were delegated almost unlimited authority, they having power to examine corporation affairs as completely as any board of directors, and to require changes in methods of operation and even reduction in prices charged for service.

Other states are following the precedent established by Massachusetts and New York. Wisconsin already has such a commission appointed under an act of the legislature, which is well worth perusal by any one desirous of learning the present-day radical trend of opinion. There is little doubt but that before long, *nolens volens*, most or all the states in the union will have commissions appointed to control and regulate at least the so-called public utility corporations. That such commissions have the right and power to determine rates, has been established in New York state by the courts, in the Saratoga case.

How, then, are these commissions to deal with the corporations in protecting the public, and at the same time give the investor every encouragement for profit, and the business no lack of opportunity? In this connection it is important that the engineer inform himself just what is the difference between operation, regulation, and confiscation.

With regard to operation, public utility commissions should restrict their action to general principles; they should not interfere with details, otherwise they will remove the present responsibilities from the shoulders of the directors to their own shoulders, restrict and hamper the efficiency of the organizations, still the incentive to work, and destroy the reasons for promotion of the employees—all of which will result in depreciating the service rendered the public and the financial standing of the corporations themselves. As has been well said:

> Regulation should stop where operation begins. Matters of business discretion should be left to the decision of those who are responsible for business results.*

If state regulation is to determine rates and limit the earnings upon investment, it may logically be asked, should the state not also include a guarantee of reasonable returns on the investment? If a corporation takes all the risks, it is logically entitled to all the profits. If the state prohibits anything more than a definite profit, may it not be morally bound to assure that profit? In fact, municipalities have been known to go a long way in this very direction by granting an exclusive franchise, which affords a monopoly and prevents competition.

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* Report, Committee Public Policy, N. E. L. A., 1907.

The principle of state control is not new, although its application has recently been greatly broadened. We have become so accustomed to considering liberty as unrestricted license for all, that the statement of Chairman Stevens of the New York State Commission, at the dinner of the American Institute of Electrical Engineers in February, that the public can demand and take from the individual, much less the corporation, anything "from his pocket book to his life inclusive", was as startling as true. The only precedent to the taking, is the public necessity and the proper manner and remuneration. In theory, then, regulation is correct, if only the practical application to the concrete case were not so difficult.

Confiscation means the taking of property without allowing "fair return" thereon. Fair return is a smooth legal term which neither the courts nor anyone else has yet been able precisely to interpret. In the decision of the United States Circuit Court in the Columbus case, an unallowed demand for a reduction in electrical rates, a decision with which every engineer interested in public utilities should be acquainted, it was stated that, over and above legitimate operating expenses and depreciation charges;

> The owner of the property should be at least permitted to receive as his compensation for its use the legal amount of interest allowed by the state of Ohio.

The court then goes on to say:

> It may well be doubted whether the legal rate of interest is reasonable and just compensation to the owner of the property devoted to public use, etc. * * * It may well be doubted whether capital would at any time for this legal rate alone be willing to enter upon the rendition of public service of the kind performed by the complainant under these circumstances and conditions., etc.

Again in the famous case against the Consolidated Gas Company of New York, in which a reduction was sought from $1.00 to $0.80 per thousand feet of gas. The court has held that the owner is entitled to "a fair return upon the reasonable value of his property", which is guaranteed to him by the famous fourteenth amendment to the Constitution.

Apparently, the existing state commissions realize the importance of a comprehensive, thoroughly considered, and reasonable line of action based on "well settled principles of public policy"; and they feel the necessity of proceeding cautiously in order to establish correct rulings and avoid the charge of confiscation.

But the radical feeling of the time, as well as some unexpected conclusions, are indicated by certain rulings of the several state commissions with regard to public utility corporations. These are worth considering as illustrating general conditions which the engineer must bear in mind when advising his client as to investments and earnings.

The commission of the second district of New York states that they have:

> Refused to consider the application of foreign (other than those incorporated under the laws of the state of New York) gas and electrical corporations to do business in this state, and have announced it as a rule that no application will be entertained.

The Wisconsin statutes provide that only corporations organized under the laws of that state shall receive franchises therein. It seems to me that this is a somewhat narrow policy which can not be long continued without modification.

The same New York State Commission has decided to accept as satisfactory, unsealed electric meters having not more than 4 per cent. of error, although requiring gas meters to be within 2 per cent. of correct, and sealed by a representative of the commission. It is doubtful whether the leniency of the commission toward electrical operating companies will compensate the manufacturing concerns for the odious comparison made of the electric meter with the much slandered gas meter.

The same commission announces unequivocally that it will require each corporation to maintain a depreciation fund which must be provided out of earnings. This is a very wise conclusion required by the statutes of some states, and a step which many corporations have failed to take, as they should have done for the protection of their security holders.

In the Lockport decision the New York State Commission established an important precedent; they allowed the consolidation of two competing companies, but prohibited, as prescribed by statute, the issuing of securities to an amount exceeding the total capitalization of the two old companies. Thus it appears, losses resulting from a war of extermination and the increased cost of consolidation cannot be met by the issuance of new securities, as formerly, which is from one standpoint radical and far-reaching. Again, the commission ruled that the low prices reached through competition should not be increased after consolidation, the consolidated company agreeing in writing not to raise rates except with the consent of the commission, after further rehearing, which precedent, if uniformly followed, while protecting the public, possibly might tend towards bankruptcy for some consolidated companies.

As the result of its experience, the Massachusetts Gas and Electric Light Commission has recently reported that it finds the benefits of the consolidation of gas and electric companies in cities of considerable size do not compensate for the disadvantages to the public arising from such consolidations.

The engineer, of course, well knows that it costs more per unit to deliver gas or electricity to the small consumer than to the large consumer, yet the New York Commission of Gas and Electricity that went out of existence last July fixed a maximum kilowatt-hour charge to be made by the Rockland Light and Power Company in Orangetown. It has been shown that out of 112 customers served at a loss under the rate formerly charged, 75 would receive service under the new rate at a greater loss to the company; while out of 26 served at a profit, 19 must be served at an increased profit to the company in order to make good the losses increased by reduction of price to the 75 mentioned above. It is hardly necessary to say that the courts would not sustain this ruling, as was proved in the well-known Columbus case. The present commission has, by petition, taken under consideration an order to restore the old rates.

A consideration of the rulings of state commissions shows a tendency to place all corporations on the same footing as regards the returns to investors; that is, regardless of whether capital has been invested in a judicious and intelligent manner or in an inefficient way, the precedents established indicate that about the same profit will be allowed in either case. This, of course, does away with all incentive to improve the earnings by cutting down operating expenses, or to decrease the price, or introduce new apparatus or modern methods. It removes the stimulus heretofore existing with the individual, to make the very best showing possible, and hence is a reasonable, valid, and practical objection to control by commissions. One method of offsetting this very decided disadvantage has been evolved by the application of the London sliding scale, so-called because originating in London, England, and now in use in Boston. The principle is a profit-sharing one, in which the investors are entitled to a definite rate on their investment with a fixed price for their product to the consumer. Every decrease in price, as for example 5 cents per unit in the case of gas at Boston, entitles the investors to an increase of one per cent. in their rate of dividend. An objection to this plan is that while it may be perfectly fair for a term of years, improvements in methods of manufacturing may so largely reduce the manufacturing costs as to entitle the investors to abnormally large dividends, at which time a readjustment of the base for price of product and rate of dividend would result in seriously depreciating the securities held by the owner at the time of such adjustment. This London scale, however, is at present the best practical method evolved for automatically adjusting profits as between the public and the corporation.

*Franchise valuations.* In considering the expenses and profits of a public-service plant, the engineer must determine the proportion of earnings to be applied to taxes and dividends, the amount of both of which will usually be affected by the value of the company's franchise. At present the franchises of different corporations are variously valued at from less than nothing, or a liability, up to a $20,000,000 asset. Therefore, the competent public corporation engineer must understand what a franchise is, its dollars and cents value and its distinction from the good-will of a going organization, favorable contracts, or physical property.

A franchise is a license, granted by a state or municipality recognizing the right of a public utility corporation to do certain business along prescribed lines. As the privileges and earning power of franchises vary, so their values vary. On one extreme it has been argued that because a franchise costs nothing, or is supposed to cost nothing, it should not be valued or capitalized by a corporation—the present New York statutes prohibit capitalization of franchises by new corporations—because then the public is forced to pay, by increased cost of service, the fixed charges on what they have themselves once owned and gratuitously bestowed. The corporation replies that its franchise is regularly and heavily taxed. If it has no value, it cannot fairly or logically be a subject for taxation; if it has value, it can and should be capitalized. The answer made to this is that the franchise tax is included among the items which go to make up the proper selling price of the corporation's product, and therefore is indirectly paid by the customer without in any way affecting the stockholders' investment or profit.

On the other hand, as the engineer well knows, franchises are frequently granted as a sort of bonus to induce capital to undertake, perhaps at a loss at the start, certain operations for the benefit of itself and the public. One purpose in accepting such obligations has been, not immediate return, but the profits to be gained in the future by the growth of the town or state and the consequent increase in revenue. As time goes on, the value of the franchise increases the same as real estate, or a desirable business location, and it would seem might be just as logically recognized as of value and capitalized.

Granted that certain franchises have become enormously valuable, corporations should not be disparaged on that account. If the public gave away something for nothing, they did so because they were unable to secure any price for it, or they failed to recognize its value and made a poor bargain, or their officers betrayed their trust. Under any of these suppositions the corporations may stand blameless, and are perfectly entitled to their franchises and the value of them. It is but a few years since it was impossible to interest capital in the construction of the New York City Subway; finally, privileges were offered as an inducement and the construction completed, which has proved a notable financial success. Should any one now claim that because the investors have profited largely the contract should be annulled? Yet a few weeks ago the startling doctrine was advanced by a public service commissioner that we of to-day are not bound by an agreement of yesterday, that:

> A common council or a legislature may barter away any present rights, yours or mine, for to-day. But the future is not theirs to give. They may not dispose of rights which belong to our children as much as to us, and to their children and their children's children after them. They may allow private development and management for the sake of immediate public advantage, any such investment must be scrupulously protected; but the franchise itself is something which may not be given away because it is not within the province of the Legislature to give away that which does not belong to the existing community.
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> A franchise granted by the legislature of fifty years ago belonged then to us of to-day quite as much, if not more, than to our grandfathers, who handed it over to some railroad in perpetuity. It belongs to us now, as it will belong to our grandchildren in their turn. The action of the legislature of two generations ago in giving away our birthright is not morally a binding contract upon us to-day when it comes in conflict with present or future public interests, and the vested rights of the private inheritors of that franchise will not stand when they come in conflict with the vested rights of the whole people of the State of New York.
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> This may not be 'good law' now, but I believe it will be in a very short time, for the public perception has grown very swiftly of late. And the courts of law are never very far behind public opinion. Some legal way will always be found sooner or later to do what is morally right.

If the commissioner is correct the engineer must know it, and figure a large annual depreciation on the value of franchises; he must ask when does the last generation's rights end and to-day's begin; on what day after granting does the legislature's perpetual grant cease, is it to-morrow or day-after-to-morrow, or next week, or when? Doubtless the commissioner is influenced by the trend of both public opinion and some recent court decisions emphasizing the right of public necessity as against individual or corporate welfare. Perhaps he is overwrought by intimate contact with the oppression resulting from certain grants; but, however rapidly we may have grown in socialistic doctrine, the engineer cannot agree that obligations can be broken simply because they are onerous. He recognizes that the franchise granted 50 years ago had neither the opportunities nor responsibilities of that same franchise to-day. New conditions beget new obligations, which the corporation must meet or the franchise may become valueless on its hands.

Aside from feeling or argument in the matter, the courts have held, and will doubtless always hold, unless it is expressly excepted, that a franchise is property and a more or less valuable asset. If, then, the franchise is property, what may be the value of the property? The present secretive, uncertain, inequitable, unscientific method of arriving at the value of each corporation's franchise, as practised by the State of New York, for example, is, to use the language of the courts themselves, " little more than a guess " and should be replaced by something simple, logical, uniform, and publicly determinable.

It may be right to prohibit the capitalization of future franchises beyond what they have legitimately cost, but the engineer interested in seeing a " square deal " should oppose any attempt to destroy by fiat legislation the value of franchises already established. In many cases there can be no objection to letting the corporations evaluate their own franchises, because the necessity of offering their product at a reasonable selling price on one hand, and, on the other hand, meeting the taxes that may be imposed by the public, will, in the end, generally establish a fair value for a given franchise. Where state commissions have been appointed with large powers to control and regulate public utility corporations, it will be necessary for them to determine a value for the franchises of the various companies under their supervision. Thus far, no logical or uniform method of evaluating franchises has been determined upon by tax assessors, the corporations themselves, the public utility commissions, or the courts.

The more common method of evaluating a franchise that has prevailed, especially among those interested in owning and selling corporation securities; namely, considering the franchise as worth the difference between the value of the physical property of a corporation, and the market value of its stock and bonds, can hardly be considered tenable, for the following reasons:

1. Because in such valuations is included not only the franchise value but also the worth of good-will, favorable contracts, business organization, etc.

2. Because the daily fluctuating price of stock and bonds due to general business conditions, market manipulations, or stock jobbery, make it, as a practical matter, extremely difficult to determine the fair market value of a corporation's outstanding stock and bonds.

3. Because the market value, even if correctly determined, does not indicate, in many cases, the real value of a corporation's stock and bonds. The market value of said securities often depends upon the success with which printer's ink and promoters' efforts have succeeded in impressing the mind of the public, which is generally ignorant, intentionally or carelessly, of actual operating and financial conditions.

The wide difference of opinion among the courts, and the general uncertainty as to the proper method of setting about fixing franchise valuations, is illustrated by the contradictory conclusions reached by the two different officers of the courts who have attempted to place a value on the franchises of the gas companies operating in New York City. The Master who conducted an exhaustive hearing in the matter decided that the franchises were worth $20,000,000. Judge Hough, of the United States Circuit Court, who reviewed the Master's report, concluded that the same franchises were worth $12,000,000. Certainly there should be some fair method evolved for more closely approximating the real value of a given franchise than the wide divergence indicated by these figures. The rule of law under which this country operates is not based on an opinion, guess, or the discretionary rule of an individual, even though clothed with governmental authority. The action of courts, assessors, or commissioners, must be restricted as far as possible to forming conclusions based on definite and fixed laws. It would seem as if the engineering profession, as a disinterested party, appreciating the necessity for and relation of a franchise to a corporation's business, might assist in evolving some method of fairly and logically fixing franchise valuations. The following is suggested with that thought in mind.

Starting with the premise that on one hand the investor in electric and gas utility securities has been demanding a return of from 9 per cent. to 15 per cent. on the actual investment, as shown by the testimony in the Consolidated Gas case from such witnesses as Messrs. Emerson McMillin, N. W. Halsey, Samuel R. Bertron, Allan B. Forbes, " bankers having much experience with gas properties in their investments ", and on the other hand that the courts, as indicated for example in the Consolidated Gas case and the Columbus decision, are inclined to base their decision of " fair return " upon the investment, upon the legal rate, which varies from 5 per cent. to 8 per cent. in different states, we have the extremes of earnings considered fair; namely, from 5 per cent. to 15 per cent. on the actual investment, depending upon location.

For purposes of discussion herein, consider a corporation operating in the state of New York, where the legal rate which, at least, will be allowed by the courts as a "fair return" is 6 per cent. In view of the fact that the capitalist has indicated that he will not be interested at 6 per cent., but that perhaps 9 per cent. would be attractive, are we not safe in assuming that with a New York corporation he would be content with 8 per cent. when he knows that his property will be defended from unfair taxes and competition through protection afforded by a state commission? The nature of the business, compared with other enterprises, is such that the return of 8 per cent. upon the investment actually made by a public utility corporation would not seem unreasonable. Now if the capitalist will accept 8 per cent., and the court will stand by the legal rate of 6 per cent., we have only to prove that the value of the franchise—which the courts have uniformly admitted should be considered as of value—is worth one-third the amount of the actual investment to secure an allowance of 6 per cent. on the whole, or 8 per cent. on the actual cash investment.

An examination of the values placed on many franchises in the past for purposes of taxation, capitalization, condemnation, or court decision, will indicate that perhaps an average valuation of the franchise in each case is not far from one-third of the actual replacement value of the corporations assets. This ratio, though somewhat arbitrarily assumed, would seem under present circumstances to be both a fair and reasonable one for existing franchises. If it is a middle ground on which the various conflicting interests could meet, we will have an automatic, easily determinable, open and above-board method of evaluating franchises. As will be recognized, the proposed method gives a different value to the franchises of different companies, but is equally fair to all because based on their tangible value: it will also be seen that the value of the franchise of a given company may vary from year to year, depending upon the value of their property. Both of these variables are essential in a franchise valuation.

Example illustrating "fair return" for New York corporation.

| Life of franchise | 20 years | Perpetual |
|---|---|---|
| Cash investment or replacement value | $300,000 | $600,000 |
| Capitalization of franchise at 33% | 100,000 | 200,000 |
| Total capitalization | $400,000 | $800,000 |
| All operating expenses, 40%-50% gross | 36,000 | 96,000 |
| Maintenance and repairs, 7% on 66% investment | 14,000 | 28,000 |
| Depreciation fund, 5% on 66% investment | 10,000 | 20,000 |
| Amortization on franchise value, 5% | 5,000 | ...... |
| Interest on total capitalization, 6% | 24,000 | 48,000 |
| Gross income | $89,000 | $192,000 |

In making up the annual operating and fixed charges of a corporation, it is proposed that the state commission should consider the value of the franchise, as determined above, allowing the legal rate thereon and also a further amount for depreciation or amortization, depending upon the life of the franchise. This latter figure, in the case of a perpetual franchise, would be nothing; but in the case of a short-time franchise would be a very appreciable amount, which of course must be paid by the public. The economy of a perpetual franchise, which the companies desire, will be appreciated, and there is no great objection to it, provided its owner is properly restricted so as to safeguard the public interest. To illustrate the foregoing, let us consider a concrete example of a New York corporation which has been granted a liberal franchise for a period of twenty years, and has invested $300,000 in order to establish a going business, compared with a similar corporation having a perpetual franchise and an investment of $600,000 For more fully illustrating conditions as found, we will assume that the general operating expenses, in the first case are 40 per cent. of the gross income, and in the second case, 50 per cent. due to differences in apparatus installed and efficiency of management. Repairs and maintenance will be taken at 7 per cent. and depreciation at 5 per cent.

If the gross income exceeded the above figures, the price of the corporation's product should be reduced proportionately to a prearranged increase in dividends, in accordance with the London scale or a modification thereof. If the gross income were less than the above, it would be proper to increase the price of the commodity, as was authorized, for example, by the Wisconsin Public Utilities Commission in the case of the LaCrosse Gas and Electric Company.

It will be noticed from the above example, that in a different state with a different legal rate the returns allowed on the investment, and consequently the gross income allowed, would be different. This is as it should be, because the rate of return varies in different parts of the country, as is recognized by the various legal rates in the different states.

The plan suggested for regulating corporations does not place all the corporations on exactly the same basis at the start, as indicated by the example given, due to difference in efficiency of apparatus or management; but these differences are probably not greater than those which arise by reason of location, business opportunity, or public sentiment, and will doubtless about offset one another independently of the fact that the effect of the London scale properly applied has a tendency to bring all companies to the same earning basis.

If some definite plan for determining " fair return " in connection with franchise valuation, could be agreed upon and urged by any considerable proportion of disinterested people conversant with the facts, or even the corporations themselves, would not the commissions and the courts be inclined to accept and adopt such precedent thus established? The result would be a definite knowledge of what returns from public utility corporation investments could be counted upon, and what valuations would be accorded their tangible and intangible property, ignorance of which facts is the principal reason for the present unsettling of their business, undervaluating of their securities, and to some extent the discrediting of the work of the engineer.

## DISCUSSION ON "THE ENGINEER'S ACTIVITY IN PUBLIC AFFAIRS —PUBLIC UTILITY COMMISSIONS AND FRANCHISE VALUATIONS." NEW YORK, APRIL 10, 1908

**George S. Coleman:** In one respect I agree with Mr. Floy, engineers as a class are, perhaps, a little too modest; but I do not quite agree that engineers ought to be considered in any wise responsible for matters which are hard enough for other men to handle, men who are devoting all their time to it. I do think, however, that the time has come when groups of engineers, different kinds of engineers, should give the benefit of their concerted thought and action to any public question on which they are supposed to be especially well informed. In the case of a new bridge across any of our rivers, or a new subway, or a new elevated railroad, in fact any kind of engineering work likely to affect the public, this Institute, and every body of engineers who in any way might be related to that enterprise, should be heard officially. If Mr. Floy's suggestion this evening shall encourage among engineers the habit of not merely quiet, independent thought in their work, but concerted action after discussion, he will have accomplished a notable result.

I do not quite agree with Mr. Floy as to the constitution of public service commissions. In a country like this, where we are dealing, or called upon to deal, with a body brought into existence through the legislature, and representing the legislature as a sort of permanent committee, what is wanted is men who are intelligent, who are open-minded, who have had some experience in affairs, who are patient, who are thorough, who are industrious, and who have good judgment. Now, I would just as lief commit the affairs of the public service to a body of engineers as to any other body of men whose profession compels them to think, and whose training and experience tends to make them impartial. About three-fifths of the average legislative body are lawyers: that happens to be the present proportion on the public service commission for this district. It has been said that the difference between the common law and the statute law is that the common law is the perfection of reason and the statute law is made by the legislature; this is a legislative enactment and legislative enactments will have to be submitted to until a better law can be framed But I do not agree with Mr. Floy as to the necessity of having experts as members of the commission. To follow that line consistently there would be needed as commissioners not only railroad men, gas and electrical experts, but expert accountants, expert financiers, experts on labor, and on every other subject that necessarily comes before the commission. Depend upon it, if there are three lawyers, or any number of lawyers on any commission, no agreement will be reached without discussion. With three engineers the same might be true, but I do not know from experience. I am willing to leave the composition of the commission to any body of intelligent men who have the necessary qualifications.

On the subject of what a commission should do, I must again differ from Mr. Floy. He cites with approval a quotation to the effect that where *operation* begins *regulation* should stop. If that were taken literally, after the commission has given an order to one of the transit companies to do certain things, like vestibuling cars, keeping cars in better condition, running more cars, or making more stops, regulation would be ineffective if it ceased where operation began. The commission for the first district employs a large body of competent engineers, the eyes, you might say, of the commission, a body of engineers of whom all engineers should be justly proud—men doing their duty well and faithfully, and without prejudice. These men report to the commission what they find and suggest what in their judgment would improve the operation of any public utility corporation. Their reports are submitted in condensed and accurate form, and if the commission may act of its own motion it will, after due consideration, act promptly. If any matter requires regulation, an order will be issued accordingly; if it does not, the matter will be dismissed. Although these things do not always appear in the newspapers, there are many improvements made by many public service commissions which are the direct result of suggestions of citizens or of the inspectors of the board of engineers connected with the commission itself. If the regulation is to be at all effective, details must be carefully considered.

As to the value of franchises, that is still an unsettled question. I sometimes think that the mechanism in the heads of the judges and lawyers and experts has stopped on a dead centre: it is going to require some little pushing one way or the other to bring to an end the question as to the proper way of valuing franchises. We have had some recent experiences in trying to value franchises for the purpose of taxation, and it is not an easy matter. Reputable men will be found who differ honestly as to the proper way of valuing franchises. In three different cases, tried one after another, involving different points, a practically different result was reached in each instance. We have as yet no final decision by our courts. It does not follow because a corporation has invested many millions in plants which have been superseded or duplicated or thrown aside and new plants substituted, that it should earn necessarily a fair return on all its investments. Even the Supreme Court of the United States does not approve of that theory. There is a vast amount of what is known as "lost capital" that cannot be recovered. If Mr. Floy's proposition, with which I agree, is sound, that a corporation already in existence should be treated the same as a new corporation entering the same field, then, of course, as an inevitable result, all the capital expended and taken out has been lost, unless possibly it has produced a *good will*, which, with respect either to a gas company or to some railroad companies, is almost a contradiction in terms. In this city, for instance, there is a railroad company having an excellent franchise. Originally, it was constructed as a horse railroad and operated as such for many years, and then turned into a cable road, and then, not long after, all the cable apparatus was removed and it was turned into an electric road. In 1900, when the Special Franchise Act came into effect here, there had been $26,000,000 represented by capital stock, $35,000,000 represented by bonds, and some floating indebtedness outstanding, and yet according to the appraisements made by the company itself, the total plant—tracks, roadbed, power house, and electrical apparatus—could be duplicated for about $10,000,000. There was a frightful waste, apparently and actually, of good money which never could be made up, unless that company should be treated differently from a new company starting with $10,000,000 capital and a similar franchise. Let us be thankful that we do not have to decide that question to-night.

The other suggestion in connection with the subject of the franchise was, that if a corporation should be restricted to earning what is called a fair return on its capital, and every corporation is treated on the same basis, improvements may be discouraged. But the modern theory seems to be that where there is state regulation a monopoly is not dangerous. It might well happen that one great gas company, one great electric company, one great transportation company, in the Borough of Manhattan, would be sufficient and would not be objectionable if it were wisely regulated. That would do away with one objection of Mr. Floy's resulting from competition, or lack of competition, if all corporations were to be treated alike.

A friend of mine, a lawyer, said to-day: "I sometimes wish very much that I could go out and deal with *things*, instead of with *ideas*." The more one deals with ideas, except as those ideas are related to practical things, the more at sea one becomes. I agree with Mr. Floy that engineers have been too modest, but in other respects I have to differ with him.

**Chas. F. Lacombe:** In discussing Mr. Floy's paper possibly more value will attach to these remarks if it is stated that my past experience has been largely in the line of building, operating, and managing lighting and power plants, and that in entering the city's service it was entirely from a non-political standpoint, my work being purely of a professional character. During the last five years in the city's service a number of important discussions have come up, in which my particular work was involved, and, in consequence, I have been in close touch in these matters as they have occurred.

In discussing this paper, one may assume probably that public supervision of public utilities corporations by commissions or other bodies is necessary and has come to stay, not on the theory that all corporations are bad or that even a majority are bad, but on the theory as shown by experience in late years, that wise and far-seeing regulation of public service is necessary to prevent the sacrifice of the service later on to the demands of that portion of the financial world which apparently requires great profits from stock speculation to the detriment of everything else. The present New York street railway situation is a shining example of this, as well as of a law as to transfers that is almost disastrous.

It has been said that the public gets no better service where there is public supervision, than it does where there is no supervision: that is a question that depends largely on the kind of control exercised. We will also need time to improve and perfect a method we have only just begun to use. This criticism may be true in a limited sense where the companies are working on a high plane, not only for the benefit of their stockholders, but for good service to the public. But the idea that there should be no public supervision because there are many of these companies, if carried to the limit, could be compared with the fact that we pass laws against crimes, not because the great majority are criminals, but to protect that majority against the very few who are.

It is also the duty of a public service commission to stand between the company and the public when the public demands are unfair or impossible. Some of the most difficult work the engineer has to do in public service is to prevent demands being made, mainly from ignorance, which are impossible to fulfil. It is our duty at times to protect the public against itself. This may sound odd, but a very good example is the present police traffic regulations.

From personal experience, I thoroughly approve Mr. Floy's contention that there should be some engineering representation on these commissions. Their work certainly comprises supervision of the most important engineering enterprises in the district which they control, and even one well equipped engineer of what we might call "general administrative engineering experience," would be a great aid to the commission in rendering unnecessary, if the term may be used, the conduction of the entire commission through matters of technique, which the engineer could settle at once, thus saving much time for the whole commission and giving them a clearer view of the main point at issue.

In reply to this, in discussing it with attorneys on a friendly basis, they are very apt to say: "Well, assuming that the board is made up with no engineering representation, they can hire engineers." The reverse of this proposition would be equally true, that if it were made up largely of engineers, it could hire representatives of other professions. In a way, business men and other professions seem to regard the engineer in the light of an expert only, in a limited field, and that beyond this he has had little experience and has little knowledge of the affairs of the world at large with which they think they are more closely in touch. It is hardly necessary here to point out the large number of what might be termed "administrative" engineers, actively engaged in managing, at least in part, not only the engineering side but the business side of a great number of the enterprises.

The engineer advising a commission of non-engineers not being a member of the body, would certainly be compelled to exercise the greatest care and conservatism in expressing opinions, which might be misconstrued in discussion among men who were not engineers. Nor would such an engineer take the responsibility which he might take as a member of the commission. This fact, in my experience, has been noted a number of times. The salaries offered by the State for engineers serving the commission, but not members, would not attract the men that could be secured as commissioners by the honor and dignity of the position. A commission dealing largely with engineering subjects, therefore, made with a proper representation of lawyers, engineers, and business men would, I think, be of more value than one in which either element was left out.

From lack of careful engineering consideration due to hurry and rush caused by public clamor, regulations have been passed by commissions and by the legislature itself, which could well be termed "inexpert legislation," and which the courts have rejected. This appears entirely unnecessary, and involves a waste of large sums of money. Much time and trouble would be saved in long and expensive lawsuits which have come from just this form of error. If an experienced, conservative engineer, with the power he would have as a member of such a commission, had been in touch with the matter he could probably have prevented a number of such cases in the past, for public clamor and government by newspapers would naturally not appeal to him as against his knowledge of the laws of nature. In support of this, I would call attention to an example of inexpert legislation, of which we have heard a good deal.

This is the suit of the Consolidated Gas Company against the attorney general, the district attorney, and the New York State Commission of Gas and so on, and also the City of New York, as contesting the constitutionality of Chapter 736 of the Laws of 1905, and Chapter 125 of the Laws of 1906, this latter law being known as "The 80-Cent Gas Act."

The Gas Commission set the price of gas to the private consumer at 80 cents in the city of New York, and the price of gas to the city for its own purposes, at 75 cents per 1000 cu. ft. A decision has now been rendered against the city by the United States Circuit Court, Southern District of New York, which will be appealed to the Supreme Court of the United States, for the settlement of certain points as to constitutionality. A great deal of pressure, as voiced by the newspapers, was brought to bear on the commission. If the commission had had an engineering representative of high standing it is probable that, taking into consideration the success of the sliding scale for gas companies in England, some such sliding scale would have been adopted here, instead of making a direct cut from $1.00 to 80 cents, and to 75 cents in the case of the city itself. This reduction might have been extended over a period of years, so that the increased consumption of gas, which seems inevitably to result from a decrease in price, would have convinced the companies that they would not be taking the risk of having to operate at a loss.

There is also in this law the requirement that gas shall be supplied at a pressure of not less than one inch, and not more than two and one-half inches in *any service main at any distance* from the place of manufacture. As a matter of fact, to-day modern gas appliances require really a higher pressure than the minimum set, and the city itself in requiring the operation of gas lamps is put in a peculiar position, in that it is forced to require a minimum pressure of one and one-half inches in order to operate the mantle lamps at reasonable efficiency, whereas the legislative act allows the company to fall to one inch pressure before the company is penalized. In Manhattan, with the very considerable rise in grade between the lowest point and the highest point, the rise in pressure due to the height of the column of gas will alone force the gas pressure beyond the legal limits. The Consolidated Gas Company tried to operate within the legal limit, and they found that when they did they received a large number of complaints from people who could not operate their gas stoves and cook their meals on account of low pressure. The penalty for any violation of this condition was $1,000 for each offense. It has escaped my mind now as to how many times the companies were found above or below the pressure required, but the last time it was looked up, and that was a year ago, the penalties would have amounted to a very large sum.

The candle-power of the gas was also raised from 20 to 22, which seems unnecessary, and if the gas fell below this candle-power, the company was to be penalized by a fine of $1,000 for each offense. This also added materially to the cost of making gas.

Further than this, in the same law—Chapter 736 of the Laws of 1905—the companies were also penalized $1000 per offense in case they even sent a bill to the City of New York for over 75 cents per 1000 cu. ft. I cannot tell you the figure to which these fines would reach in case they had all been enforced rigidly and an attempt made to collect them.

The United States Circuit Court in its final order declares that all these penalites are unconstitutional and void, and are not to be enforced. More than two years' very hard work was put in by both sides in this case, and the joint expenses of the city and the company will amount to a large sum. Meanwhile the people of the city of New York have received little if any benefit. I think I can say safely that if it had been left to a board having one or more competent gas engineers as members, these errors might have been avoided, and the price to the consumer gradually reduced.

In addition to these matters, caused by inexpert legislation, the Supreme Court of the United States has recently rendered a decision in what is known as " The Minnesota Case," in which they state that the laws as passed by the legislature in the State of Minnesota affecting railroads and warehouses, contain certain penalty clauses which would act to prevent the railroads and warehouses from going into court at all, and, in consequence, these penalites are unconstitutional and void. Beyond that they refer the matter back to some other court as to the propriety of the rates involved, in the following language:

> It cannot be to the real interest of any one to injure or cripple the resources of the railroads of the country, because the prosperity of both the railroads and the country is most intimately connected. The question of sufficiency of rates is important and controlling, being of a judicial nature it ought to be settled at the earliest moment by some court, and when a Federal Court first obtains jurisdiction, it ought, on general principles of jurisprudence, be permitted to finish the inquiry and make a conclusive judgment, to the exclusion of all other courts. This is all that is claimed, and this, we think, must be admitted.

It is apparent, therefore, that penalties which are not legal and reasonable will be considered very carefully by the courts in these matters. While the Consolidated Gas case does not show any clauses preventing the company from having its day in court, it does show penalties imposed on the disobedience of conditions which are impossible or unreasonable. One, if not two, of these conditions would have been condemned by engineers.

Decisions of this character certainly point out that legislation affecting public service corporations must be fair and reasonable, and should be made by men who know something of the engineering and operating conditions. They point out forcibly the necessity and propriety of having a skilled and experienced engineering member in a public service commission.

Mr. Floy also takes up the interesting question of franchises, what they are and what their valuation should be. To bring this matter up to date, I have procured and will read to you some definitions given of a franchise in the last decisions of the United States Circuit Court in the Consolidated Gas Case, as rendered by Judge Hough, and also as to the valuation of the Consolidated Gas Company's franchise.

It appears that, apparently, the question as to whether a public service corporation is entitled to add the value of its franchise to the tangible assets on which a fair return would be lawfully demanded, is to be submitted to the Supreme Court of the United States for the first time. The United States

Circuit Court points out that the investment of property in a manufacturing plant was made, not *in* the franchise, but *under* the franchise, and on the faith thereof. In speaking of the ways in which the value of a franchise can be stated, the court says, speaking probably of the usual methods of obtaining franchises:

> On every private sale of franchise property, the price paid is so much money lost to the public by official incompetence or worse, and such sale can confer on the vendee no right to compel the consumer to repay him a price which should have been paid to the State. For these reasons I believe that, on principle, the franchise should be held to have no value except that arising from its use as a shield to protect those investing their property upon the faith thereof, and that considered alone and apart from the property which it renders fruitful, it possesses no more economical value for the investor than does the actual shield possess practical value apart from the soldier who bears it.

The court then states that many decisions have been rendered, the trend of which is against his own views, but that for good reasons he must follow the weight of authority. He says:

> I conclude, therefore, that I am compelled to consider franchises not only as property, but as productive and inherently valuable property, and to add their value, if ascertainable, to the complainant's capital account before declaring the rate of return permitted complainant by the statute complained of.

In a later decision, after the re-opening of the case for certain reasons, speaking of his valuation of the franchise, the court says:

> It is not difficult to detect flaws in findings opposed to the settled opinions of the judge who happens to constitute the court.

The court in its first decision then goes on to the question of valuing franchises, and says that, for the purpose of condemnation or regulation:

> The value of the franchise depends wholly upon what is earned under it, and I believe the best way of finding out how much a franchise separately considered is worth, is to ascertain what those persons desirous of continuing operations under it consider it to be worth. In a corporation whose stock is freely bought and sold, such value is measured by the success attending the sale of stock based entirely upon capitalization of franchise, yet the value of stock issued only in consideration of the franchise is obviously dependent on earnings after the stock based on tangible property has received a satisfactory dividend.
>
> This is really the same measure of value that the New York Franchise Tax Commissions are using, except that instead of that reasonable return upon the tangible assets deemed by the commission as sufficient, there is substituted the opinion of the investing or speculative public as to what constitutes a satisfactory rate or return upon all stock. Thus, if the investment of a hundred thousand dollars in a franchise protected business authorized, in the opinion of the promoters, the issue of two hundred thousand dollars' worth of stock, and such stock for a number of years maintains itself at par, paying satisfactory dividends, it would be obviously fair to assert that in the opinion of the share-holders that franchise is worth one hundred thousand dollars, assuming no depreciation of tangible assets. Yet it will always be true that unless the whole net return, compared with the value of tangible property, is above a satisfactory return on the tangible investment alone, the addition of stock issued for franchise will be regarded as "water", and detract from the value of the entire issue, and I think this is conclusive proof that value in a franchise depends wholly on what the actual investment can earn.

> I consider the real reason which compels me to consider the value of franchises to be that for generations it has been the universal practice of American Corporations, supported by the opinions of courts and counsel to capitalize their franchises for all it was thought traffic or business would bear, until the country is full of share-holders whose certificates of stock are based upon the belief that in some way or other such certificates were legally created pieces of property and would, like other property be protected by Federal and State constitutions.

The court then goes on to value the franchise at this date on the basis of the valuation in 1884, when the Consolidated Gas Company was started, proportioned to the value of personality and realty of thirty million dollars, the investment at that time in tangible assets. He finds the investment in tangible assets in 1905 is forty-seven million dollars, and the franchise valuation proportioned thereto would be twelve millions, which he allows. The court explains this in his later opinion, in which he states that the franchises of 1884:

> Might as well have been valued at twice the amount of stock then issued. It was nothing but an attempt to capitalize expected profits; but the attempt now has twenty years' success to justify it.

Further on he defines franchises as follows:

> The so-called franchises may be denominated " licenses, or tenancies at will " or " continuing trespasses ", yet what is being done under them is a fact, a profitable thing, a taxable property by the law of this state, The State of New York, therefore, is estopped from continuing to tax that property by one set of representatives and denying it all value through the instrumentality of another.

The contention of the city of New York in this matter was that the franchise had value as regards condemnation or sale, but that it should not have value when it capitalized that value and charged a return upon it against the public that gave them the franchise.

It will be very interesting to note the decision when it is given by the Supreme Court of the United States, and it is to be hoped that it will go into the question of what is the proper way to value a franchise, particularly when, as stated, this has come before the court practically for the first time, strange as that may appear.

I trust that I have not quoted too much law, but I thought that it would be of service to bring in some of the decisions which have been rendered since Mr. Floy wrote his paper, and I also thought that it might be of value to a number of engineers who are at times confronted with similar problems.

**H. M. Brinckerhoff:** This question of the necessity of co-operation between corporation officials and the public service commission was made a prominent part of the speech of Commissioner James E. Sague, of the Second District of the State of New York, at the annual banquet of the Stevens Alumni Association. He said:

> Satisfactory results can only be obtained by cordial co-operation between the corporation officers and the commissioners in the same spirit which was exercised in the conference between the Interstate Commerce

> Commission and the corporation accountants in the preparation of the uniform system of railway accounts recently adopted. . . .
>
> In all departments of the commission's work the same necessity for co-operation is apparent. We all need to be educated in this field. We can probably learn much from Europe, and especially from England, where the Board of Trade has functions similar to those of our commissions. The commissions need all of the intelligent advice that they can get, and all criticisms if kindly made, will be received in an humble spirit. We want to know where to begin in our work. We want to learn what is most important to be done now, and what ought to be left for the future, and we need especially perhaps to learn where to stop.

This is the carefully considered, positive statement of the only technical member of the New York State Public Service Commission, and when it is considered that Mr. Sague has had long experience in railroad operation as well as large corporation affairs, it forms a very striking argument for exactly the idea we are advocating.

Our public utility boards and railroad commissions to attain full usefulness should have upon them some experienced men, men who have been through the mill and who will not ask the impossible. No man, no matter how sincere and devoted, can grasp in a few minutes, operating questions with which he has never had actual personal experience.

The great variety and complexity of questions coming before public regulating boards require for proper balance a membership representing legal, financial, and commercial experience, but equally important is it that some experienced operating members should sit upon these boards in order that a proper appreciation of the effect of proposed orders and regulations may be considered and clearly appreciated by the board during its deliberations.

At this point I part company with the author in that I do not agree with his contention that commissioners should be primarily and exclusively engineers, and I doubt whether this was in the mind of Mr. Perkins when he made the remark:

> A Railroad Commission should be composed of railroad men who can deal with the questions arising in a practical way.

The questions which come before boards of public control are 90 per cent. operating questions in the sense that they affect directly or indirectly the methods of, quality of, or remuneration for, operation. I have no fear that legislation or the rulings of utility boards will reverse the laws of gravity, strength of materials, or even the design of rail-sections; but I do fear that their action in certain instances will have an unexpected detrimental effect upon the very service which they were hoping to improve, a result which experienced operating men would clearly foresee.

Purely engineering questions should be handled by engineering experts who are making a specialty of the particular line momentarily under consideration. Mr. Floy's remark in regard to hired experts seems to be a condemnation of all consulting engineering work, as there should be no difference in the amount of responsibility assumed or service rendered when acting for a public commission, a corporation, or a private individual. No one engineer-member of a commission could expect to keep up with the vast intricacies of all the engineering questions which might come before the board, whereas a practical, experienced operating man who had had the daily, monthly, and yearly running of a plant or system under his charge, would have sufficiently good judgment and experience in engineering matters to know when he must call upon an expert engineer and properly to select such an expert.

There can be no question that in many instances where public service commissions make rulings adverse to the company, which afterwards prove unwise, it is quite as much the fault of the company as of the commission, the company not having fully laid before the commission the actual facts in the case. In this connection the attitude taken necessarily, or perhaps we might say customarily, of presenting matters to a commission in public meeting as they would be presented before a criminal court, brings about an unfortunate result.

It is probably impracticable at the present time to expect matters of this kind to be considered openly in a fair, candid discussion, but if such a course could be pursued I am satisfied much better results would be obtained than by the formal, legal methods now pursued. Our commissions would very seldom go radically wrong if they had the real facts placed clearly before them. Two conflicting, cleverly concocted, partisan statements, on the contrary, befog rather than clarify the issue.

Every operating man knows that to make the worst appear the better reason, while it may be a triumph of legal skill, is not a satisfactory method of deciding operating questions. There may be differences of judgment, but an accurate basis of facts is necessary for the protection of both parties to a controversy. A short cut to a correct result would in many cases often be made by the presence on the board, as has been suggested, of experienced operating men, and I am greatly in hopes that we will see before long the appointive power fearlessly used to place upon these commissions carefully selected men of this class to coöperate with and assist the otherwise excellent personnel of which the commissions are composed. Such appointments would not only be just to the railroads but beneficial in the long run to the public.

**Louis A. Ferguson:** I heartily concur with Mr. Floy's views as to the desirability of having thoroughly trained and well equipped men of technical knowledge and broad experience upon the various commissions entrusted with the duty of regulating rates or the conduct of business by public utility corporations. It appears to be the trend of modern legislation to take from the various legislative bodies, city councils, etc., the power of regulation of public service corporations, and place it in the hands of commissions. This is extremely desirable, not only from the viewpoint of the corporations, but of the public as well. Attempted regulation of public utility corporations by large, unwieldy governing bodies such as the board of aldermen of large cities like New York, Chicago, Philadelphia, or Boston, is seldom satisfactory either to the corporation or the public. Such bodies rarely number among their members men of sufficient technical knowledge and training to enable them to pass upon the questions involved with any degree of satisfaction. For instance, when the regulation of the rates to be charged by a telephone company, a gas company, or an electric lighting company comes before a body of men numbering from fifty to seventy, it is almost impossible sufficiently to educate so great a number of men in any reasonable period of time so as to enable them to pass intelligently upon the questions involved. Usually many months, and often years, are spent in hearings before such bodies, and finally a rate is established which is not infrequently but a compromise between the rates proposed by corporation and the board of aldermen; it is not a rate based upon a thorough, scientific basis of reasoning. During all this time the affairs of the corporation are in a disturbed condition, its directors cannot plan any extension of business, the proper financing is made much more difficult, and stockholders become alarmed at the various reports as to the probable action in regard to the fixing of rates. How much more satisfactory and how much fairer is a hearing for such a purpose when conducted before a properly equipped commission appointed either by a legislature or by a governor, a commission numbering say three, five, or seven, all of whom, or at least a majority of whom, are thoroughly trained engineers, possessed of a scientific knowledge of the subject under discussion, and able, of their own knowledge, to arrive at an absolutely fair result, fair both to the corporation and to the public.

Practically everyone will concede that a public utility corporation is entitled to a fair return upon its investment. The chief difficulty encountered is the varying views of different people as to what is meant by " fair return ". Some extremists contend that the legal rate of interest fixed in any state is a fair return for public service corporations doing business in that state, while others contend for as high a rate of interest as capital can secure by engaging in any mercantile or other legitimate enterprise. In my opinion neither of these views is correct. There are but few capitalists that would care to engage in any industrial enterprise, such as manufacturing, where the returns upon the investment would be less than twelve per cent. A review of the returns made upon capital invested in banking enterprises throughout the country shows a very high return of interest upon the capital invested, in many cases running as high as twenty, thirty, fifty, and in one case at least as high as one hundred and twenty per cent. No one will seriously contend that a public service corporation is entitled to so high a return upon its investment as is referred to in the case of banks; nor, on the other hand, should anyone seriously contend that such a corporation is entitled to, say, only five per cent. return upon its investment, five per cent. being the legal rate of interest in the State of Illinois. It is axiomatic that the return upon capital invested in public service corporations should be sufficient to entice capital. There is no magic about a public service corporation or about the business in which such corporations engage which will serve to attract and interest capital, unless the return upon the money invested be approximately that which might be earned upon the money if invested in other legitimate enterprises. It is my opinion that public service corporations would be and should be satisfied with a lower rate of interest upon their investment where their rates and other business dealings with the community are controlled by a commission, small in number and composed of, say, trained engineers, than they would deem satisfactory if their rates and other business dealings were controlled, as they are now, by state legislatures or boards of aldermen. In the first case the corporations may be reasonably sure that no radical measures will be advocated by a commission which would serve to throw unnecessary burdens upon the corporation, or which would prevent the corporation from earning a fair return upon its investment. In the second case the corporation is compelled to exist in a constant state of uncertainty, never knowing what wave of radicalism may strike the community and be reflected in its lawmaking body, whereby public clamor may result in the fixing of rates so low as practically to amount to confiscation, or in the surrounding of the business with such so-called safeguards or other provisions relating to methods of bookkeeping, etc., as to make it, if not extremely difficult, at least extremely expensive to operate its business in a satisfactory way and in compliance with the law.

Too much stress cannot be laid, however, upon the absolute necessity of appointing as members of state commissions entrusted with the regulation of the affairs of public service corporations, men of undoubted integrity, the highest order of ability, and possessing the confidence of the community. In fact, the members of such a commission should be the same class of men, so far as their standing and ability are concerned, as we expect to find in the Supreme Court of the United States. If these commissions are to be made fat berths for politicians, public service corporations have only jumped from the frying-pan into the fire. The temptations and possibilities for wrongdoing in such a position are enormous, and weak or unscrupulous men occupying such positions would have it in their power either greatly to oppress the corporation or so greatly to favor it as to create much dissatisfaction in the community, a state of affairs which would eventually result disastrously to the corporation.

There is no doubt that the sentiment of the public is now undergoing a marked change in its views toward public service corporations. We have passed through an era of radicalism during which the public regarded large public service corporations in the light of public enemies, and believed that no measures were too severe to be directed against the corporation and no restrictions too rigid to be thrown around them. It was formerly thought that competition was the thing, and that by granting a license to several gas companies, several electric lighting companies, or several telephone companies, much better service and much lower rates might be secured. It has been discovered that this theory is entirely wrong, and it is now rapidly becoming the sentiment of the public that the best interest of the public is served by a properly regulated monopoly. It has been discovered that whenever two or more public service corporations engaged in the same line of business are serving the same community, they are not likely to remain separate very long. Duplication of plants is a waste of capital which is not economic, and, if persisted in, necessitates a much greater outlay for cost of operation. If there is *bona fide* competition between two such corporations, it means a war of annihilation until the weaker of the companies is forced out of the field. This militates against good service and also prevents conservative capitalists from investing money in public service corporations doing business in a community where such a state of affairs exists. Where a public service corporation may be assured of a monopoly, or a practical monopoly, of the field, it may very well consent to do business at a much lower rate of interest upon its investment, because the fear of irresponsible competition is removed and the business may be conducted with an exact knowledge of all the factors entering into the cost of conducting and maintaining the corporation and prosecuting its business.

The remarks of Mr. Floy upon the desirability of engineering experts equipping themselves for service upon state commissions and the advisability of the various societies and similar bodies of engineers taking an interest in public affairs with a view to having their members placed upon such commissions, commend themselves to me, and I am a firm believer in the advisability of adopting such a policy on the part of our engineering bodies.

**Henry L. Doherty:** There is so much to be said both for and against public control of public service corporations that nothing short of a large volume would cover all of the important things which might be considered. Therefore, I shall touch briefly on only one or two points of first importance.

Public opinion is such that perhaps public control of public service corporations is inevitable. It would seem self-evident that the scope of this control should be the least possible to insure protection to the public. The recent tendency of some of the public utility bills, however, seems to anticipate public general managership rather than public control.

The broader the scope of control attempted, the less efficient will be the work of public control; and an attempt at too much breadth will defeat the whole scheme of public control. If public control is inevitable, this control must be shaped so as to make its disadvantages the least burdensome and its advantages the most beneficial. To insure impartial decisions the executors charged with public control should be as far removed as possible from the influence of public opinion.

Public control, however, is apt to convince the owners and managers of a quasi-public corporation that only the minimum returns may be earned and distributed. And this interpretation of public control removes all incentive on the part of the owners and operators of quasi-public corporations to make proper effort for economies and improvements. The so-called "London Sliding Scale"—which is a very incomprehensive name to a very comprehensive subject—is an attempt at a reasonable division between the public and the owners of the property for improved results. For public control to be a success, it must be automatic as far as possible, and the company must be rewarded by higher returns for improved results. The best plan for the accomplishment of this end can, I believe, be secured by, and demands, engineering consideration.

The men charged with this work must have an extraordinary degree of intelligence, or else a combination of experience in the business which they are expected to control coupled with a high degree of intelligence.

These executors are generally constituted as commissions, and they in turn must have a competent staff of accountants, statisticians, and experts. The success of the plan must rest primarily with the fairness and intelligence, not only of the commission itself, but of all their various assistants. Under modern conditions a public service commission cannot do either intelligent or effective work without competent engineering advice or assistance. This I think is generally recognized, and the commissions accordingly have their engineering staffs. But in selecting the commissioners themselves the engineering profession should not be overlooked as a very likely source of the best available timber.

**W. W. Freeman:** With respect to the question as to what would be the best make-up of the public service commission, I have no suggestions to offer. I have found no difficulty in agreeing with some things that have been said by each of the speakers. As one who does not claim to be an engineer, I entertain no fear whatever from the standpoint of having the engineers represented on the commission. At the same time, I should be equally anxious to have a thorough representation of broad gauge business men who would view the situations presented from the executive and business standpoints, entirely aside from engineering or technical ideas.

I agree with Mr. Floy that the matter of determining the value of a franchise is likely to adjust itself when it has been definitively decided that the valuation admitted for the purpose of taxation is equally available as an asset upon which a fair return can be earned.

In the matter of a fair return, Mr. Floy apparently thinks that six per cent. is admitted from the legal standpoint, that nine per cent. or more is asked for by the investing public, and that eight per cent. would probably be acceptable, and that the franchise should be fixed at a valuation that will make up the difference. If the franchise has a legal valuation the companies are entitled to the return on that valuation, whether it be for property that is intangible or tangible; and it would seem that if we are claiming eight per cent. or any higher per cent., we must of necessity in justice to our own interests ask and demand that return upon the fixed valuation of the franchise the same as on the tangible property.

It seems to me that the plan of fixing the gross income which a company shall be entitled to earn, after its expenses, plus depreciation and plus six per cent. of eight per cent. return, leaves altogether out of consideration the fundamentals on which the business is based. The first consideration in public service regulation doubtless ought to be a demand for good service. I think we will all agree to that. Then of course comes the demand for a reasonable charge, which is admitted; and then the question of a fair distribution to the stockholders, which is also admitted. But equally important with these three is what amount over these items must of necessity be assured to the company for permanent and successful operation. There are years when the revenue will be less than in other years, and any company that disburses all of its earnings in its good years will have no earnings to disburse in the poor years. The maintenance of a permanent investment requires of necessity some reserve, and in addition there are the expenditures attaching to extension work and improvements. These vary with the company, and the idea of the company earning only the amount which it needs for distribution to its stockholders seems to me to be ill considered. I believe that public control should be exercised over, not so much what the company earns but the amount disbursed, and what it does with the balance. For instance, a company that has a capitalization of $1,000,000 and earns and distributes, say, over and above expenses, eight per cent. on $1,000,000, distributes $80,000 a year, and that company requires $50,000 or $100,000 a year for the extension of its business in new work. Now, whether that company issues additional capital during each year to take care of these extensions, and pays the same rate of dividends upon the total capitalization, or whether it earns a sufficient amount to enable it to pay a fair rate of return to its stockholders, and also a sum beyond that which will enable it to take care of its extensions and additional capital, is the same thing to the public, but it means a great deal of difference to the company. I feel that it would be very much more conservative management, very much more in the interest of both the corporation and the public, if the company should be able to manage its business so that it could take care of reasonable expansion independently of its ability to raise further capital from year to year, so long as it is supervised in respect to its charges and its disbursements, and what it does with the surplus. If that plan were followed, it would be very much in the public interest as well as in the interest of the company.

**George S. Coleman** (by letter): I should like to add a comment on that part of Mr. Floy's paper in which he says:

> A perusal of the minutes of the hearings held before state commissions will convince any unprejudiced person that a disproportionately large amount of evidence and testimony is submitted, in the consequent unnecessary financial expense and consumption of time for the purpose of explaining terms, apparatus, and methods of operation and expenditure to commissioners who, in general, should be acquainted with the matters being considered.

In justice to commissioners generally it should, perhaps, be said that their official duties require them not only to decide questions but to preserve a record of the testimony submitted, and to make the record intelligible to those who are not experts. In an ordinary suit at law technical terms have to be explained for the benefit of court and jury. The commissioners must fortify their findings by a proper record, so that if their decisions are challenged they may properly defend them. While this involves tedious inquiry it seems almost essential to orderly procedure.

**Henry Floy** (by letter): It is a pleasant surprise to find so much agreement among the engineers, if not among the lawyers, with the views expressed in my paper. Even Mr. Coleman agrees with my opinions more fully than perhaps he seems to admit, when he says:

> I would just as lief commit the affairs of the public service to a body of engineers as to any other body of men whose profession compels them to think, and whose training and experience tend to make them impartial.

I do not for a moment wish to convey the idea that various engineering specialists, experts in particular departments, should make up a commission. I do not argue that an electrical expert, a specialist, should properly be a member of the commission, or as Mr. Brinckerhoff seems to understand, that "commissioners should be primarily and *exclusively* engineers." I would consider a mechanical engineer, if he knows something of electrical work, hydraulic work, gas work, and has had experience in the operating and commercial departments of a public utility corporation, much better qualified to make a good commissioner. The same way with the railroad man. What is wanted is not an expert designer of cars or locomotives, but an engineer experienced in railroad organization and operation. Mr. Coleman makes the too common mistake, which I referred to, of considering a man with a technical training capable of passing on technical questions only, whereas such training is, frequently, merely the basis for success in commercial and economic affairs. I do not argue that a commission should be made up, entirely, even of widely experienced engineers; that would be as erroneous as constituting it of lawyers or business men. Neither can I see any necessity for three out of five members of a commission being lawyers; for a large amount of the work of a commission has nothing to do with law, as such, while much of it has to do with engineering questions. From my experience before commissions, I believe more helpful and practical results would often be accomplished in a simple and expeditious way by following procedure which might possibly be termed engineering rather than legal. Why questions involving matters of an engineering nature cannot be best answered by a commission constituted partly of men who are conversant with engineering affairs, I cannot understand. My plea is for a balanced commission consisting of engineers, business men, and lawyers.

With regard to operation versus regulation, Mr. Doherty's discussion very completely expresses my view.

Mr. Brinckerhoff's ideas and my own, as to the value and propriety of retaining consulting engineers, are, I believe, identical. My thought was that the responsibility for a decision must rest upon the commissioners; it should not on any plea be shifted by them to "hired experts", however competent, either as consultants or as direct employees.

As I understand Mr. Freeman, it does not seem to me he quite appreciates some of the points I have tried to bring out. There is no getting away from the fact that commissions are being appointed and franchised valuations are being determined. One need not agree that one-third is the correct valuation of a franchise, but some valuation must be fixed; and it seems to me we need to study this question and try to determine the figure that will be reasonable and fair to both sides. Purely as an illustration, I have suggested a franchise valuation of one-third and a rate of six per cent. because in some cases that is a fair valuation and rate; and we may be able in some instances to get the opposing sides to compromise on these figures. Of course, as an Institute we do not want to stand committed to six per cent. or any other per cent., but as a practical proposition it is comparatively easy to get money to invest at eight per cent. if the investing public is assured that it will be protected in an eight per cent. net return. In the past the New York public service corporations may not have been able to get investors interested on an eight per cent. basis, but they will be able to do so in the future if their interests are protected by a commission.

I agree with Mr. Freeman as to the necessity of a reserve account, which, however, together with other similar items, was covered, in my thought, by the percentages allowed for "maintenance" and "depreciation." The amount and itemizing of these several details is, of course, immaterial for the purpose of here illustrating a method of determining franchise valuation. I differ with Mr. Freeman as to his suggestion that a public service corporation should provide for its expansions from earnings; I had supposed it was now pretty generally agreed that extensions should be charged against the capital account instead of being made a part of the charges for service.

*A paper presented at a meeting of the Pittsburgh Section of the American Institute of Electrical Engineers, Pittsburgh, Pa., May 6, 1908.*

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# CALCULATION OF THE STARTING TORQUE OF SINGLE-PHASE INDUCTION MOTORS WITH PHASE-SPLITTING STARTING DEVICES

BY I. E. HANSSEN

The starting torque of any induction motor is proportional to the product of the main field by the quadrature field, hence to the product of the main electromotive force by the quadrature electromotive force. The starting torque of a single-phase induction motor with a phase-splitting starting device can, therefore, be predetermined if the electromotive forces at the terminals are known.

If we have a Y-connected motor, we first calculate the starting torque which the motor would develop on a three-phase circuit; in this case the above product is $e^2 \frac{\sqrt{3}}{2}$ and the area of the electromotive force triangle is $e^2 \frac{\sqrt{3}}{4}$, where $e$ is the terminal voltage.

The actual torque of the motor on a three-phase circuit is

$$T_3 = \frac{3\, e_0^2\, r_s}{Z^2\ 746}$$

where

$e_0$ = Impressed electromotive force per phase.
$r_s$ = Secondary resistance per phase reduced to primary terms.
$Z$ = Total impedance per phase.

If the same motor is now connected with a resistance reactance starter as shown in Fig. 1, the electromotive forces at the terminals can be found as follows:

Referring to Fig. 2, lay of $OA$ and $OB$ representing the impedances $Z+Z_2$ and $Z+Z_1$, respectively. Draw a line in the direction $OD$, the angle $BOD$ being equal to $AOC$ and angle $EBO$ to the angle $BOC$, $OC$ being in the direction of the resultant of $OA$ and $OB$. $OE$ is then the joint impedance of $Z+Z_1$ and $Z+Z_2$.

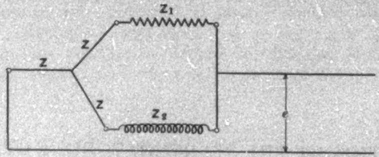

Fig. 1

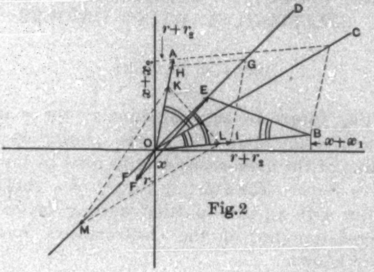
D
C
r+r2
A
G
H
K
x+x2
E
O
L
I
B
x+x1
r+r1
x
F
F
r
M

Fig. 2

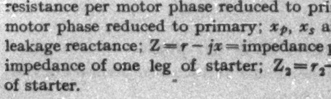
STARTING WINDING
Z1 = r1 − δx1
MAIN WINDING
Z = r − δx
e

Fig. 3

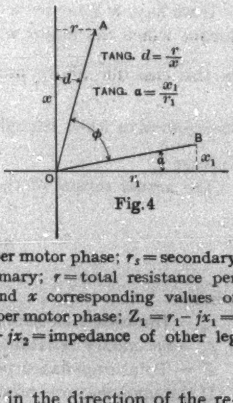
r
A
TANG. d = r/x
d
TANG. a = x1/r1
x
φ
B
a
x1
O
r1

Fig. 4

$e$ = line e.m.f.; $r_p$ = primary resistance per motor phase; $r_s$ = secondary resistance per motor phase reduced to primary; $r$ = total resistance per motor phase reduced to primary; $x_p$, $x_s$ and $x$ corresponding values of leakage reactance; $Z = r - jx$ = impedance per motor phase; $Z_1 = r_1 - jx_1$ = impedance of one leg of starter; $Z_2 = r_2 - jx_2$ = impedance of other leg of starter.

Draw $O F$ representing the impedance $Z$. $E F$ is then the resultant impedance of the motor and starter.

Divide this into the line voltage; this gives the total current, which is to be laid off along $O D$ to some convenient scale, giving $O G$; resolve $O G$ into $O H$ and $O I$, the currents in $Z Z_2$ and $Z Z_1$.

Lay off $O K = O H \times Z$ and $O L = O I \times Z$, representing the drop in the two motor phases connected to the starter. Lay off $O M = O G \times Z$, the drop in the third motor phase.

The triangle $K L M$ now gives the values and the relative phase relations of the terminal electromotive force.

The starting torque on a single-phase circuit is

$$T_1 = T_3 \frac{\text{area of triangle } K L M}{e^2 \frac{\sqrt{3}}{4}}$$

If the motor is delta-connected use equivalent star values and proceed as above.

In case we have a motor wound as shown diagrammatically in Fig. 3, $Z$ being the main winding and $Z_1$ the high resistance starting winding, we first find the starting torque of a two-phase motor having two windings like the main winding.

This is

$$T_2 = \frac{2 e^2 r_s}{Z^2 \, 746}$$

Then referring to Fig. 4, lay off $O A$ to represent the ampere-turns of the main phase, the direction being such that

$$\text{tangent } d = \frac{r}{x}.$$

Draw $O B$ = ampere-turns of starting winding,

$$\text{tangent } a = \frac{x_1}{r_1}.$$

Then the starting torque is

$$T_1 = T_2 \frac{O A \times O B \sin \phi}{(O A)^2}$$

*Presented at the Conference on the Conservation of Natural Resources, White House, Washington, D.C., May 13-15, 1908.*

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# CONSERVATION OF POWER RESOURCES

BY H. ST. CLAIR PUTNAM

Without disparaging other aspects of our progress, it is not too much to say that our time is preeminently the age of power. This applies to the world at large, but especially to the United States. Our population is increasing with unprecedented rapidity, but our mineral production is increasing so much more rapidly that some have called this the age of metal. Steel, copper, and wood are combined in mechanical devices at a rate increasing more rapidly than ore production, so that others have characterized this as the age of the machine; yet that aspect of modern life which most impresses the student of progress is the increasing use of mechanical power through the development of prime movers and the utilization of new power sources. Rapidly as our population advances, it is outrun by metal production, and that in turn by machine building; yet our most rapid progress—the feature in which our advancement exceeds all others—is in the development and use of power.

*Historical division.* Historically considered, the utilization of our power resources has undergone three characteristic phases of development.

In the first, power was produced directly by natural forces such as falling water and wind and its use necessarily was limited to those places where these natural forces were found. This led to the early manufacturing establishments of New England grouped about easily available water powers. This might be called the period of water powers, and in this country it held ascendency in the manufacturing industries until about 1870.

The second phase was characterized by the development of the steam engine which rendered practicable the utilization of the stored energy in fuel as a source of power. During this period the development of coal mines and rapid growth of our railway systems imparted a tremendous stimulus to commercial enterprise. Proximity of water powers was no longer controlling, and factories were established at points selected by reason of the availability of raw material, labor, transportation facilities and markets, as well as power supply. As in the first period, however, the power necessarily was used where developed, and the size of the plant was limited to the requirements of the individual user.

*Electric power.** Electrical transmission of power is the new art which now is resulting in another and radical change in methods of utilizing our power resources, permiting, as it does, development whether by water power or by steam at points most convenient and economical, and transmission to the consumer in form adapted to great variety and convenience and use. This new development in applied science calls for reappraisement of the sources from which our power is derived. The size of the power plant is no longer limited to the requirements of the individual user, but the power for entire communities can be supplied from a single station. The enlargement of this field of work newly opened by the electric transmission of power from great distances is now in active and practical development. As a result rapid changes are taking place in the methods of using power. New economies are possible of accomplishment and the resulting effect upon the conservation and utilization of our power resources is of the greatest importance.

*Fuel supply.* Where power is developed from the combustion of coal, wood, oil or gas, our natural resources as such are destroyed and they cannot be replaced, excepting to a limited extent in the case of wood and similar products. The supply of natural oil and gas is limited and uncertain and the amount available is required for special industries. The coal production of the United States for the year 1906 was 414,157,278 tons; for 1907, about 450,000,000 tons. If the production of anthracite coal is continued at only its present annual rate the supply will be exhausted in 60 or 70 years. Since the beginning of our coal industry the total production has doubled approximately every ten years. Assuming that this rate of increase cannot be maintained, but will become constant in about 150 years, it is estimated that the supply of bituminous coal will be exhausted in approximately 700 years.* But that the coal production should become constant even 150 years hence, implies that our industries must become stationary, unless other power resources are found. We cannot look forward to such a condition with equanimity. Without coal our domestic and industrial life is inconceivable, and our existence in great cities and crowded communities is impossible unless a substitute is devised. The future welfare of the nation requires that all practicable means be employed for the conservation of the supply of coal.

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* Electricity, of course, is not a source of power—it is simply the agent by which energy developed from fuel and water is transmitted to the mechanism which utilizes it. In speaking of electric power, therefore, it must be borne in mind that such power is always produced primarily by water wheels, turbines, steam engines, or gas engines. With reference to their source, therefore, we have only water power and fuel power to consider, but with reference to application it is convenient and instructive to compare water power, steam power and electric power; the two former being applied directly through mechanical means to the work, while the last named has its origin in one or the other of the former and is applied through motors.

*Available water powers.* Where power is derived from water, winds, and tides, only energy otherwise wasted is used. The energy thus extracted is added to our assets instead of being a permanent loss as is the case with the combustion of coal. It is now feasible and practicable to develop water powers, whereever located, for electric power. In the aggregate the available water powers of the nation greatly exceed the present power requirements, but unless there is some curtailment in the rate of our development, our water power resources, while being of great magnitude, will not of themselves solve the problem of our future supply of power. The amount of water power available in the United States is not known. Some partial estimates have been made, but these are necessarily approximate, as exact figures can be obtained only after careful survey and study not only of the existing physical conditions, water flow, and available reservoir capacity, but of the practicable auxiliary steam power that can be profitably installed. The power of Niagara has been estimated, by Professor W. C. Unwin, at 7,000,000 h.p. A partial estimate of the water powers of the upper Mississippi river and tributaries places the available water power at about 2,000,000 h.p. The southern Appalachian regions can furnish a minimum of nearly [3,000,000 h.p.* Both of these estimates can be greatly increased by including the use of regulation reservoirs and auxiliary steam plants. The water powers of New England are more fully developed than elsewhere in the country, though much remains yet to be done. In the Rocky mountains and the far west there are immense water power possibilities; in the state of Washington alone there are 3,000,000 h.p. available;† and Governor Pardee estimates that the streams of northern California are capable of producing 5,000,000 h.p. Even approximate data upon which to base an estimate of the total amount of available water power in the country are lacking, though a good start toward collecting them has been made by the Geological Survey, with the limited means at its disposal. It is probable that the water power in the United States exceeds 30,000,000 h.p., and under certain assumptions as to storage reservoirs this amount can be increased to 150,000,000 h.p. or possibly more. Much depends upon whether regulation reservoirs and reserve steam plants are included in the estimate. Both have been demonstrated to be practicable, and undoubtedly should be considered in any estimate made of the available water power resources of the country.

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* "How long will our coal supplies meet the increasing demand of commerce?" by Edward W. Parker, U. S. Geological Survey. Presented before the American Society of Mechanical Engineers, 1907.

Using the smaller figure of 30,000,000 h.p. as an illustration, to develop an equal amount of energy in our most modern steam-electric plants would require the burning of nearly 225,000,000 tons of coal per annum, and in the average steam engine plant, as now existing, more than 650,000,000 tons of coal, or 50%, in excess of the total coal production of the country in 1906. At an average price of $3.00 per ton it would require the consumption of coal costing $2,000,000,000 to produce an equivalent power in steam plants of the present general type.

The supply of water power is limited, however, when the rapid rate of increase in our power requirements is considered, and great care, therefore, must be exercised to insure the preservation of our water power resources and to secure the maximum practicable development.

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* "Water Powers of the Upper Mississippi and Tributaries," and "Water Powers of the Southern Appalachian System," by M. O. Leighton, Chief Hydrographer, U. S. Geological Survey.

† Computed by F. G. Moorhead, in *The World's Work*, April 1908, p. 10091.

*Total power used in United States.* Using the data furnished by the census returns of 1900, 1902, and 1905 as a basis and applying the prevailing rate of increase in the industries included in these reports, and adding an equivalent amount for the steam railroads, it is estimated that the total installed capacity of prime movers in all our land industries for the year 1908 approximates 30,000,000 h.p.[A] (Fig. 1.)

The average load on steam and other engines is much less than their rated capacity, and, owing to the overlapping of loads, it is probable that the total average load does not exceed one-third or one-quarter of this amount.

*Rate of increase.* During the last thirty years the total amount of power used in our manufactories and other industries, as recorded by the census, has doubled approximately every ten years. The fact that substantially the same rate of in-

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[A] The following table compiled from the latest census returns gives the installed capacity of prime movers in the United States in the industries named at the dates mentioned:

| | Installed horse power. |
|---|---|
| Manufactures, census 1905 | 12,765,594 |
| Mines and Quarries, census 1902 | 2,753,555 |
| Street Railways, census 1902 | 1,359,289 |
| Electric Light and Power Stations, census 1902 | 1,845,048 |
| Telephones, Telegraph and Fire Alarm Systems, census 1902 | 3,148 |
| Custom Flour, Grist and Saw Mills, census 1900 (omitted from census 1905) | 883,685 |
| Steam Railroads, data from Statistics of Railways, 1905, equivalent power | 3,750,000 |

These figures include prime movers only. Duplications in the way of electric, water and air motors and rented power have been omitted. The equivalent power used by the steam railroads is based upon the result of calculations made by Lewis B. Stillwell and H. St. Clair Putnam in a paper presented by them to the American Institute of Electrical Engineers, January, 1907, " On the Substitution of the Electric Motor for the Steam Locomotive," and represents the installed power house capacity required for their electric operation in the year 1905. Based upon maximum draw-bar pull, the power of the 46,743 steam locomotives in the United States (1904) averages 600 horse power (census 1905) but the power developed when averaged over the entire year approximates only 40 horse power. In order, therefore, that the estimate of total power in the United States should not be misleading, the power used by our steam railways has been taken at a figure that is comparable with the installed power in other industries as, for example, in electric railways where the installed capacity in the power houses has been taken rather than the rated power of the motor equipment, which is many times greater than the power house capacity required for their operation.

crease has existed in coal production, railroad gross earnings, freight ton-mileage, passenger mileage, and the value of agricultural products, as well as in total power consumption, is a striking demonstration of the close interrelation and mutual dependence of these great factors which, in the aggregate, measure the industrial progress of the nation.

We cannot foretell how long the present rate of increase in our industrial enterprises will continue. This will be determined by the general laws which govern industrial development

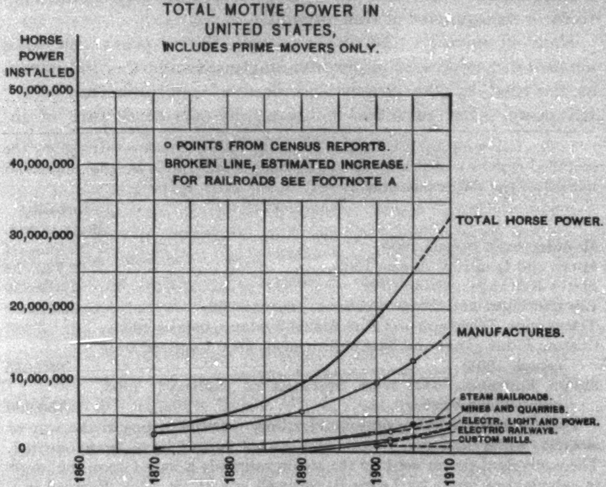

FIG. 1

and by the increase in wealth. It is clear, however, that if our power resources are exhausted or wasted the result will be disastrous.

*Relative use of steam, water power, etc.* Of the total estimated power at present produced by prime movers, about 26,000,000 h.p. is produced by steam engines, (Fig. 2) 3,000,000 h.p. by water motors, (Fig. 3) and 800,000 h.p. by gas and oil engines, (Fig. 4). These figures emphasize the present position of the steam engine in our industrial development and the relatively much less important place now occupied by water power, (Fig. 5).

*Growth of electrically applied power.* Of the total 30,000,000 h.p., including the railroads, used in the country, it is estimated that 9,000,000 h.p., (Fig. 6) or 30 per cent., is now utilized electrically (Fig. 7).* This highly remarkable growth has been accomplished in 25 years. The use of electric power at the present time is being doubled approximately every five years, as contrasted with the phenomenal doubling of the total power every 10 years. If the present rate of increase is maintained, electrically applied power will equal or exceed the power mechanically applied in 1920. This great growth is due to the convenience, earning capacity, and economy resulting from

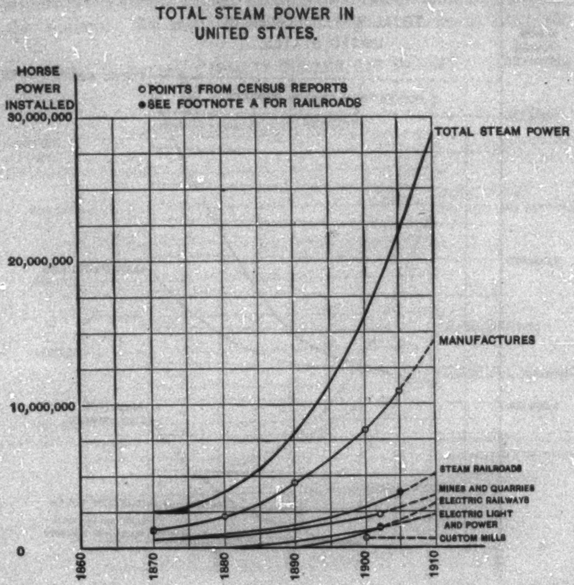

FIG. 2

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* This does not include the electric power generated in isolated plants and used for other purposes than manufacturing. These plants are not included in the census reports, and while they are individually small the aggregate electric power developed is large.

the use of electrically applied power. The significance of this remarkable increase in the use of electric power in manufactures and other industries lies in the market thus provided for the utilization of our water powers wherever located and whatever their magnitude.

*Economies due to electric power—steam power.* Where coal is the source of power, electric transmission and distribution greatly reduce the amount burned to perform given mechanical work. This results from the substitution of a few large and highly efficient boilers and engines for a larger number of relatively small and uneconomical ones and from the introduction of plant economies and skill in operation not attainable in the smaller plants. A material saving is effected also in the application of the power directly to the work through motors instead of indirectly through inefficient countershafting and belting.

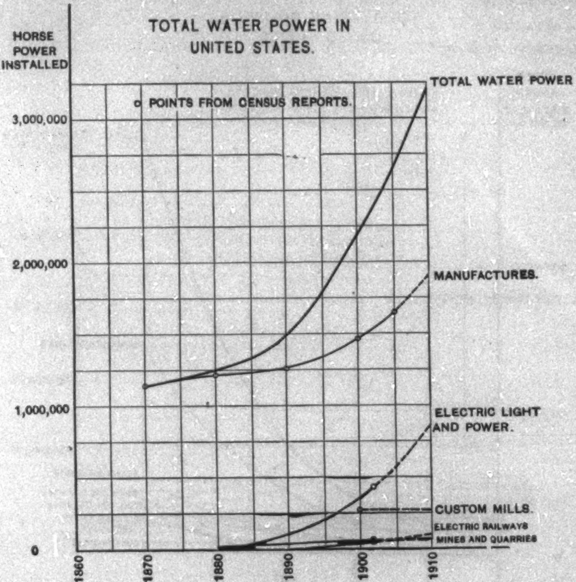

Fig. 3

A further material gain also results from the fact that a large plant carrying the load formerly carried, for example, by one hundred small plants is operated under conditions more nearly approximating uniformity of load and therefore at higher economy.

Greater economy can be obtained, even in our large plants, through the more general use of so-called fuel economizers, superheated steam, higher vacuum, and better combustion under the boilers. We may expect still higher efficiency from the development of larger boiler and engine units. These economizing appliances, which are relatively unimportant in small plants, become of great importance in large plants, and will have still greater influence on steam practice as the price of fuel increases and the cost of capital decreases.

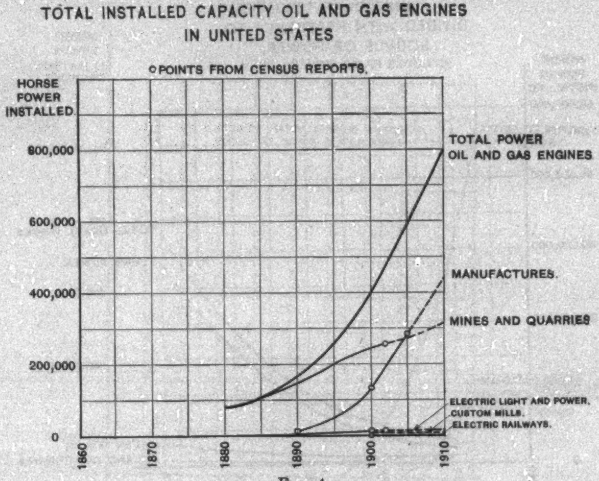

FIG. 4

*Fuel economy of gas engines.* This discussion would be incomplete without mention of the great possible fuel economy that may result from the use of gas and other similar engines. Though engines of this character antedate the use of the electric motor, their development has been slow, and they occupy a relatively unimportant place as power producers. The ordinary steam engine utilizes not more than four or five per cent. of the heat energy in coal, and our best modern steam electric plants show a heat efficiency not exceeding 10 or 12 per cent.* With the gas engine and producer gas the heat efficiency can be more than doubled, and still higher efficiency seems probable with higher compression or through the use of other possible improvements.† This is a most promising field for development and it is entirely possible that the gas engine may revolutionize our methods of using fuel for the production of power.

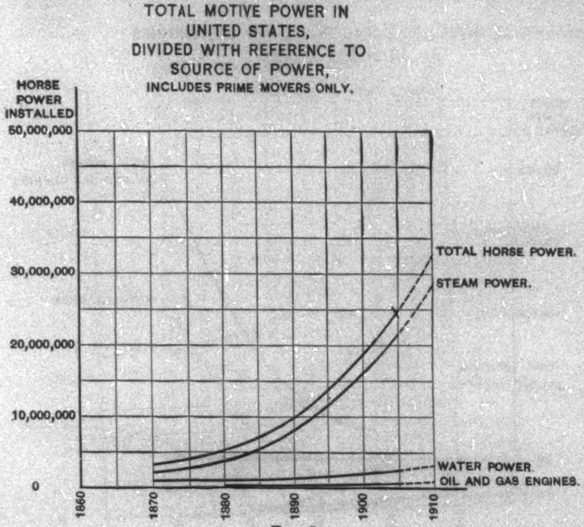

FIG. 5

Beyond these gains, which may be considered well within the limits of possible attainment by present knowledge, there stands the theoretical prospect of still greater economies, the possibility of which cannot be denied so long as methods employed in developing energy from coal results in a waste of from 75 to 95 per cent. of the potential energy which nature has stored in the coal. But the science of the present time does not permit us to assume any radical increase in efficiency of fuel engines beyond the limits which I have indicated, and our only safe course is to base our estimate upon the progress of the present time with such reasonable allowance for improved economy as is dictated by recognition of progress of the art along lines now within the horizon of possible science.

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* "Power Plant Economics," by Henry G. Stott, presented before the American Institute of Electrical Engineers, January, 1906.

† Report of F. W. Burstall to the Gas Engine Research Committee of the (British) Institution of Mechanical Engineers.

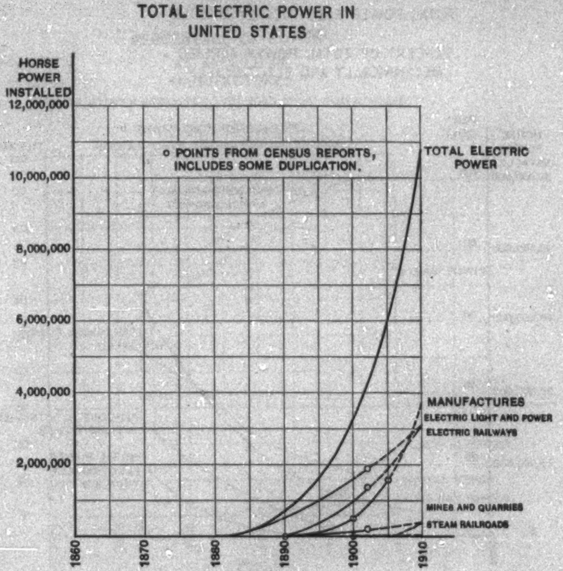

Fig. 6

*Water power economies.* Where water power is the source of supply, electricity promotes economy for reasons identical with the foregoing, except that absence of fluctuation of load is relatively less important, but the great gain which results from electric transmission is the utilization of water powers remote from power markets. Where several water powers along a stream are developed, it becomes possible to utilize, in conjunction with the larger and more cheaply developed powers, others which, considered independently, could not be utilized to advantage.

*Applications of electric power—manufactures.* Prior to 1870 the use of water power in manufactures exceeded that of steam power. Water power expressed in percentage of the total power employed has since steadily declined, falling from 48.3 per cent. in 1870 to 11.2 per cent. in 1905. (Fig. 8.) During the corresponding period steam power increased from 51.8 per cent. in 1870 to 78.2 per cent. in 1900. The census of 1900 showed a marked falling off in the rate of increase in the percentage of steam power used as compared with the rate prior to 1890, and this was accentuated in the census of 1905,

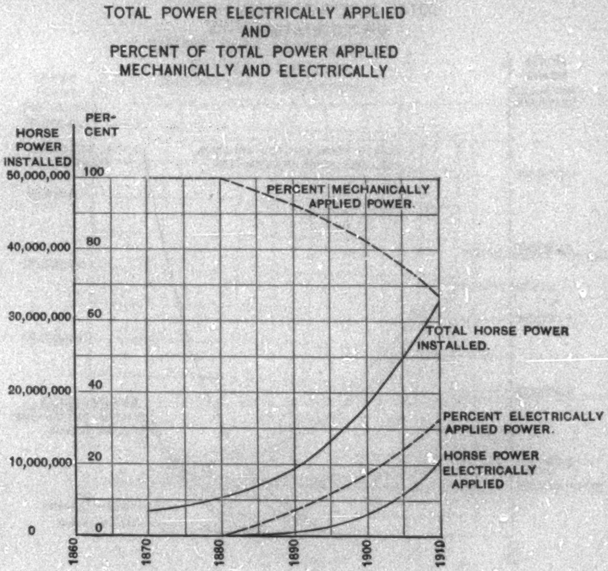

Fig. 7

when the percentage of steam power fell to 73.6 per cent. of the total. This check to the ascendancy of directly applied steam power was due to the introduction of electric power. In 1890 electric power was negligible. In 1900 it constituted 4.8 per cent. of the total. In 1905 this had increased to 11.8 per cent.—a marvelously rapid growth when the aggregate increase of over 1,000,000 h.p. in five years is considered. If the present rate of increase prevails until 1910, electric power will have reached 18 per cent. of the total and steam power will have dropped to 68 per cent. If the same rate of increase is maintained until 1930, electric power as applied to the manufacturing industries will exceed the amount of steam power applied direct.

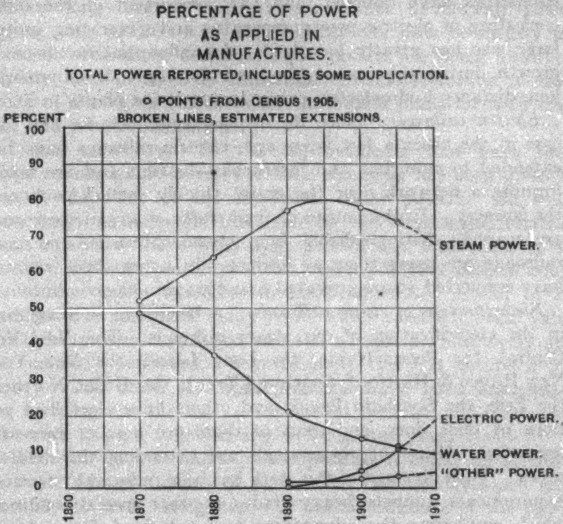

FIG. 8

*Other industries.* The tendencies illustrated by the changes that have taken place in the methods of utilizing power in manufacturing, apply generally to other industries. The increasing use of power is phenomenal; the steam engine as a source of power is thus far paramount in them all, but the percentage of electrically applied power is increasing at nearly double the rate of increase of the total power used.

*Electric lighting.* The extraordinary growth of the electric lighting industry is familiar to all. Unfortunately the results of the special census of 1907 are not yet available, but the indications are that the five years which have elapsed since the previous census will show phenomenal growth. During these five years the gross sales of the great electric manufacturing companies have doubled, and the proportion of the output consisting of electric power apparatus and generating units of large size has greatly increased. An influential factor in the growth during this period has been the rapid development of long-distance hydroelectric power transmission plants.

*Electric railways.* Since the displacement of horse and cable cars in the cities a few years ago, electric railways have been extended to suburban and interurban districts and are rapidly forming a network over the entire thickly settled portions of the country. In the nature of their traffic, many of these roads are scarcely distinguishable from steam railroads, and many railroads are using them as feeders. In a few cases railroads have converted steam operated branches into electric lines.

*Electrification of steam railroads.* A beginning is being made in the electrification of our steam railroads. The New York Central, the Pennsylvania, the Long Island, the New York, New Haven & Hartford, the Grand Trunk, the Great Northern, the Erie, the Southern Pacific and others have electrified portions of their lines, and most of these are now in successful operation. Many of these roads are extending their electric zones. Thus far most of this work has been induced by terminal requirements, tunnels, heavy grades or other special conditions which emphasize the advantages to be derived from electric operation. The increase in capacity, convenience, and greater earning power as well as the economies resulting from electric operation will stimulate the electrification of steam railroads, just as these factors have stimulated the use of electric power in other industries. The problem presented is larger because of the necessity of interchangeability of equipment, and the development must necessarily be gradual on account of the magnitude of the interests and the large capital expenditures involved. The railroads are among the largest consumers of fuel, and electric operation, exclusive of the use of water powers, would reduce the coal consumption to less than one-half of that required for similar operation with steam locomotives.*

*Tendency toward greater use of water powers.* During the past few years, there has been renewed interest in water powers on account of the practicability of their use for the generation of power and the electrical transmission of this power to distant markets. The great hydroelectric development at Niagara was the first large enterprise of this character and has demonstrated its practicability. The census of 1905 gives a partial list of long-distance hydroelectric plants developing power aggregating 600,000 h.p. and this list can now be largely increased. Our most desirable water powers are being absorbed rapidly, and it becomes important, therefore, for us to take stock of our water resources and formulate plans for their control and proper utilization.

*Inland waterways.* In the improvements that have been made on navigable rivers, too little attention has been given to the development of the incidental water powers. On some waterways, as in several instances on the Mississippi, immense sums of money have been appropriated and expended on especially difficult portions of the river. If this money could have been made available in large amounts, instead of by driblets over periods of many years, water powers of great value could have been developed and the navigation effectively and permanently improved. Unfortunately this has not been our policy. Too often the appropriations have been inadequate for carrying out the work as it should be done, and frequently the work has not followed any well-digested plan.

With the data at hand, it is impossible to make an accurate estimate of the amount of power that can be developed incidentally to river navigation. A partial estimate of the power developed at existing government locks and dams places the amount at 1,600,000 h.p.† This is based on the mean low-water discharge for three months. This subject should receive careful consideration. Improvements in navigation should be made only after thorough study of the possibilities of power development. On the other hand, many water powers are on streams that are navigable, or are capable of canalization, and these streams should be developed for power purposes only after careful examination has been made of the possibilities of the stream forming a link in the system of inland waterways.

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* "On the Substitution of the Electric Motor for the Steam Locomotive," by Lewis B. Stillwell and H. St. Clair Putnam, presented before the American Institute of Electrical Engineers, January, 1907.

† "Available Water Powers of United States Government Locks and Dams," collected by M. O. Leighton, United States Geological Survey.

*Canalized rivers.* There are many streams that are not now navigable, or are navigable for only a portion of the seasons, that can be canalized and converted into streams of great commercial value. The use of our waterways for both power development and navigation causes no conflict; these uses are in fact correlated and their interests harmonious. Where it is necessary to place a dam across a stream to develop power, the slack water so produced, with the addition of locks, renders otherwise impassable stretches of river available for navigation. Every water power development is vitally interested in obtaining a uniform flow of water. This exactly meets the requirements of navigation. The approximate realization of regularity of flow can be attained only by the construction of headwater regulating reservoirs and the preservation of our forests. Every water course that is improved for the production of power and for navigation produces, therefore, vigorous self-interested allies in the cause of forest preservation, headwater regulation, and the maintenance of conditions which are favorable to both interests.

*Canals.* Considerations which affect the use of our rivers and streams, as sources of power and for navigation, apply also to canals. Heretofore, canals built for transportation purposes have not been used, to any great extent, for the development of power. In some cases this has been on account of the limited supply of water, but more frequently it has been due to the great difficulty experienced by the animals in towing boats against the rapid current produced in the canal by the flow of water to the water wheels. In recent tests it has been demonstrated that canal boats can be towed by electric towing machines at a much lower operating cost than is possible with animals, and that operated in this manner the speed can be greatly increased.* The first cost of electric equipment is relatively large, but the change to electric towing will pay handsomely when the volume of traffic is sufficiently large. The traffic required is well within the ultimate capacity of the canal. With electric towing, the increase in the rate of current flow introduced by the development of water power on the canal is not a serious impediment to navigation.

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* "Notes on Electric Haulage of Canal Boats," by Lewis B. Stillwell and H. St. Clair Putnam, presented before the American Institute of Electrical Engineers, March 1908.

*Irrigation.* There are large areas in the Western states where the soil is of wonderful fertility, but irrigation is essential to the successful growing of crops. The cultivated lands usually lie in valleys and water is carried to them through long and ofttimes wasteful irrigation ditches. In many cases the water could be utilized for developing power on the headwaters of the streams without injury to the irrigation interests, as is illustrated by the excellent work now being done by the Reclamation Service. The development of water power will introduce another party whose self-interest dictates the use of every available method of preserving the volume of water supply, its continuity, and regularity of flow.

In some cases irrigation channels can be converted into canals suitable for at least limited navigation, and where practicable this should be done. Some types of apparatus as now developed for towing canal boats by electricity require but little space along the side of the ditch and can be installed, usually, without additional grading wherever an irrigation ditch can be constructed. Electric towing cannot be economically practicable, however, unless the traffic reaches a considerable volume. With animal power the additional capital investment is small and is proportional to the amount of business handled. With electric towing the first cost is large and manifestly sufficient traffic must be secured to meet the capital charges before profits can be realized.

*Water supply.* What has been said upon the subject of irrigation canals applies to the development of the water supply for our cities. This work, like irrigation, should be carried out so as to develop the maximum water power possible without injury to the water supply.

The preservation of the purity of water for domestic use is of great importance to the welfare of the nation. A consideration of this subject, as well as of navigable water-ways, canals, irrigation and water powers, emphasizes the absolute necessity of competent supervision of the natural water resources of the country.

*Regulation of stream flow.* The flow of water in many streams annually fluctuates between wide limits. The low-water periods limit the profitable water power development and the high periods often cause disastrous floods. On most streams the average rate of flow for the year is many times the minimum flow. It is possible in some cases to utilize a flow approximating the average by constructing controlling reservoirs on the headwaters of the stream. Our Great Lakes form a natural reservoir of this character for the Niagara River. The Upper Mississippi has great natural reservoirs which assist in regulating its flow and which easily can be made very effective in its control. The notable floods of the Ohio River can be greatly reduced by the construction of controlling reservoirs on its headwaters which will result in the saving of millions of dollars now annually destroyed. On a stream which I recently investigated the minimum flow furnishes but 200 h.p. The construction of a storage reservoir increases the continuous 24 hr. power that can be utilized to 8000 horse power. If storage reservoirs could be constructed on the Susquehanna River, upon which a great water power development is now in course of construction, so as to obtain a uniform flow throughout the year, the available power at this site would be increased from a minimum of 30,000 h.p. to 200,000 h.p. While it is impracticable to construct reservoirs capable of holding back all flood waters, it is nevertheless certain that material gain would result from well-directed efforts along the lines suggested.

*Auxiliary steam plants.* On account of the great annual fluctuations now existing in stream flow, it has been found profitable to install steam plants supplementing the water power during seasons of low water. This method on account of its expense greatly handicaps the full development of our water powers and increases the amount that must be charged for the power. Under given conditions the most profitable amount of water power to develop and the best size of steam plant to install can be determined with great accuracy. The reserve steam station need not be located at the water power; in fact, it preferably should be located at or near the market for the power when that is distant, as greater reliability and continuity of power supply is thus secured. Headwater regulation would greatly reduce the necessity for such auxiliary steam plants.

Similarly the water power which can be purchased economically by a prospective customer who already has a steam plant in operation can be accurately determined. This amount depends upon the relative cost of generating different portions of the load by steam as compared with the amount charged for the water power supplied. In its economical application this method of operation works out so that the water power plant carries the steady portion of the load where the coal consumption per horse power capacity is greatest, and the steam plant is called upon to carry the peaks only where the coal consumption per horse power is least.

*Interconnected plants.* In addition to their reserve function in time of low water or flood, auxiliary steam plants and interconnected plants are valuable as insuring the continuity of power supply. If the lines are run overhead, as they must be for long-distance transmission in the present development of the art, all electric transmission plants are subject to occasional short interruptions due to storm, lightning, or malicious mischief. It is economical and desirable to tie together two or more plants, thus greatly increasing the reliability of service. If one plant or transmission line fails the others can be pushed to take the load. From an engineering standpoint, and from the standpoint of the customer as well as the power producer, this method of operation has great advantages.

*Importance of power resources.* In 1905 the value of the product of our manufactures amounted to $16,866,706,985; the total receipts of the steam railroads were $2,325,765,167.

In manufacturing, the value of the product was $1,152 for each horse power installed, and the yearly wages amounted to $248 per horse power.

In the railroad industry the gross receipts amounted to $555 and the yearly wages to $224 per horse power, rated on a basis comparable to that used in the census report covering manufactures.

I have selected these two classes of industry for the reason that they use the bulk of the power and illustrate its tremendous productiveness in increasing our wealth.

On the basis of the lower estimate of water power already mentioned, namely, 30,000,000 h.p., and applying the ratio which now exists between wages paid and power utilized in manufacturing and railroad industries, the development of this amount of water power implies an increase in wages paid amounting to about $15,000,000,000 per annum, an amount more than double the total value of our agricultural products at the present time.

*Collection of data necessary.* These figures emphasize the vast financial importance of our power resources and the necessity of their conservation and their intelligent development. Much can be accomplished by the national government in connection with irrigation of national lands and the improvement and preservation of navigable waters. The state governments can greatly assist in this work, within their respective territories.

*Census of water resources.* A reliable census of water resources is greatly needed. The Geological Survey has accomplished much in measuring and recording the flow of streams, but the work done is small as compared with that which remains to be done. Obviously, in order that records of this character shall constitute a uniform and safe basis for the very large capital investment which must be made in the future in order that our water power resources shall be properly utilized and our fuel supplies conserved, they should be made under the immediate direction of the national government.

*Research work.* The national government can render great assistance also in the research work which it has undertaken into the better utilization of our fuels. Excellent results have been obtained by the able body of engineers engaged on this work, but when we consider that we are now utilizing but five or ten per cent. of the heat value in fuels it is evident that much remains to be done.

*Necessity of government regulation.* Power and transportation are the two great physical bases upon which modern industrial development rests. Without power our methods of transportation must revert to a level with those existing in China. Up to the present time while nation and states have regulated and in some degree aided in the development in transportation, the power resources of the country have been utilized or wasted by the private individual and the corporation with little hindrance and still less regulation by the constituted authorities. Next to individual enterprise the most essential factor in the development of our national resources is wise governmental guidance, so applied as to insure the vigorous working of individual initiative and at the same time prevent the waste by individuals of that which is vital to our national welfare and to secure in the utilization of our natural resources the highest practicable degree of economy which scientific knowledge and engineering skill can attain.

*A paper presented at the annual meeting of the American Institute of Electrical Engineers, New York, May 19, 1908.*

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# COMPARATIVE TESTS OF LIGHTNING PROTECTION DEVICES ON THE TAYLOR'S FALLS TRANSMISSION SYSTEM

BY J. F. VAUGHAN

Recent Institute discussions have brought out a decided difference of opinion on the value of certain lightning protective devices and have expressed a demand for positive data on line protection especially. This paper furnishes data obtained last summer on an operating line experimentally equipped with various protective devices. The results are of especial interest in being actual records made by means of tell-tale papers applied not only to the station protective devices but also to those on the line, and even to the line insulators themselves throughout the system.

When the transmission from Taylor's Falls to Minneapolis Minnesota, was built in 1905, local conditions demanded the best lightning protection available. The line ran southwest from the power house a distance of about 40 miles through a rolling country, partly wooded and full of lakes and swamps. It lay in the natural path of thunderstorms forming to the northwest of Minneapolis. Investigation indicated a zone about 9 miles long near the middle of the line that was especially subject to severe lightning, and the splintering of six poles in different parts of this zone before any wire was strung suggested the necessity for special protection at exposed points against direct stroke.

On account of the wide divergence of opinion on the subject of lightning protection, and the impossibility of reconciling the conflicting results of practice, it was decided to try out on the Taylor's Falls System all existing devices of promise and such others as might be devised, in order, by comparing them in actual service, to work out some effective scheme for future protection.

*Description of system.* Current is generated by four 2500-kw., 2300-volt, 60-cycle, three-phase water-wheel driven machines, each operated as a unit, with a bank of three 900 kw. transformers connected delta-delta and stepping up to 50,000 volts. The pressure is stepped down at the main sub-station on the outskirts of Minneapolis to 13,800 volts for local distribution and transmission to a steam and water power local plant

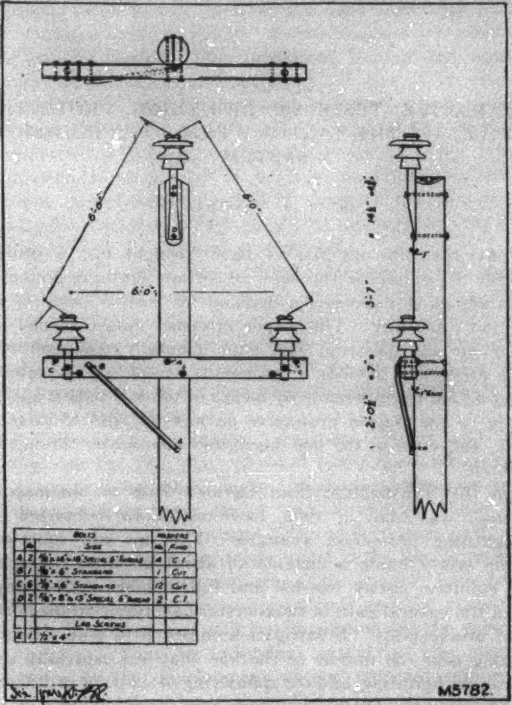

6'0"
6'0"
6'0"
1'4½"
3'7"
7"
2'0½"
F
E
C
A
D
Bolts
No.
Size
Washers
No.
Kind
A 2 5/8" x 16" x 18" Special 6" Thread 4 C.I.
B 1 5/8" x 6" Standard 1 Cut
C 6 3/8" x 6" Standard 12 Cut
D 2 5/8" x 8" x 13" Special 6" Thread 2 C.I.
Lag Screws
E 1 1/2" x 4"
M5782

FIG. 1

in the city. Automatic time-limit relay oil switches control the lines and transformers at all three plants.

The transmission consists of a single line built on private right-of-way using Idaho cedar poles of 45 ft. standard length,

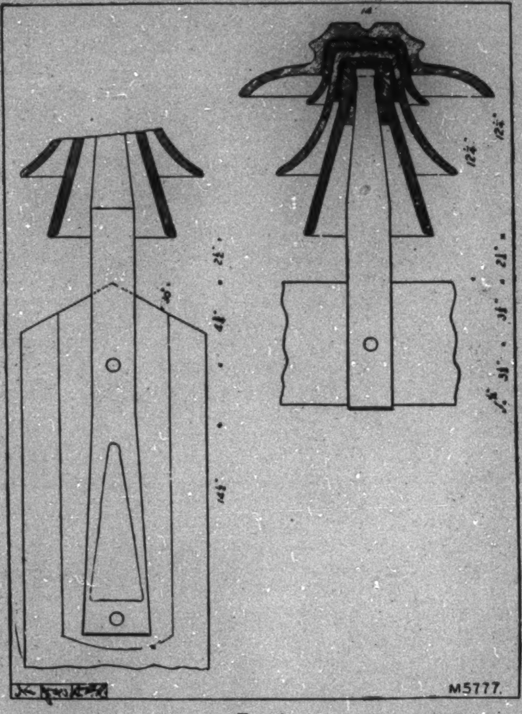


FIG. 2

carrying three 0000 semi-hard-drawn copper cables supported on 14 in. four-part porcelain insulators arranged on a 6-ft. equilateral triangle with the apex at the pole-top (Fig. 1). The insulators (Figs. 2 and 3) were originally selected from a number of samples, including five others of the writer's design,

FIG. 3—Photograph of insulator flash-over, under artificial rain test

as the only insulator obtainable which, under driving rain test, showed properly distributed electrostatic stress without concentration on any one part. These had already proved unusually rugged, as shown by two years' use, without any electrical failures on 75 miles of 57,000-volt transmission on the Puyallup system in the state of Washington. The insulators are supported on iron-pipe pins cemented into them and bolted to the pole-tops or set into the cross-arms. The line also carries a pair of telephone wires on an arm 7.5 ft. below the transmission arm.

The telephone system consists of a metallic circuit of No. 10 copper wire mounted on porcelain insulators of the same design as the ordinary double petticoat glass type. Instruments are permanently connected at the power house, sub-station, and inspector's cottage at the middle of the line, and booths provided at various points for tapping in inspectors' portable instruments.

*Station protection.* For protection of the power house and sub-station low-equivalent multigap arresters and oil-insulated choke-coils were installed, supplemented at the sub-station by a set of experimental aluminum cell-type arresters connected to the entering line through a small number of arrester gaps in zigzag arrangement, set so as to be normally active.

The transformers at all stations were further protected on their low-tension sides by static discharge gaps.

## LINE PROTECTION.

*Horn-type arrester.* Three types were installed, one at each end and one in the middle of the line, primarily to pass off disturbances of unusual magnitude, and also to experiment with the different forms.

The sub-station arrester consisted of a single gap on each phase, arranged with a sheaf of water jets forming series resistance to ground. This required too much water and was replaced by tanks of water with terminals of carbon rods in fiber tubes (Fig. 4).

The power house arrester had two gaps in series between each phase and ground, with the second gap shunted by carbon terminals placed in the river (Fig. 5).

The Hugo arrester, at the middle of the line, was built on the selective resistance principle, with three gaps in series on each leg, the second and third gaps being shunted by water-box resistances (Fig. 6).

*Overheaded grounded wires.* Four types were erected in the nine-mile zone in 0.5 mile lengths, alternating with 0.5 mile lengths of unprotected line as follows:

Type *A*. Two wires mounted on a cross-arm 5 ft. apart on either side of the top line wire and about 18 in. below it (Fig. 12).

Type *B*. Two wires supported on standards of 1.25 in. iron pipe 6 ft. apart and 18 in. above the top line wire (Fig. 7).

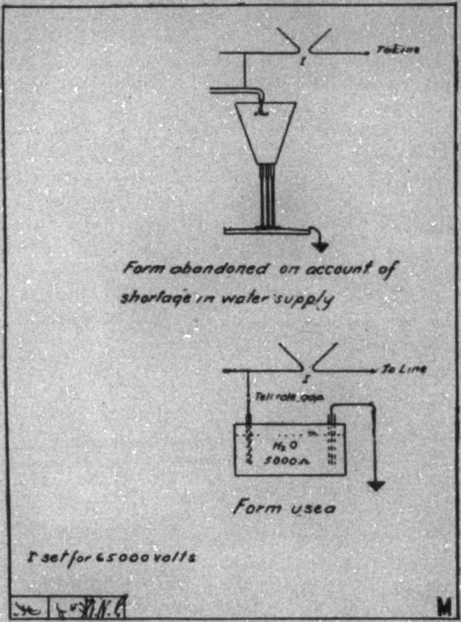

To Line
I
Form abandoned on account of shortage in water supply
To Line
I
Tell tale gap
$H_2O$
5000Ω
Form used
I set for 65000 volts
M

FIG. 4

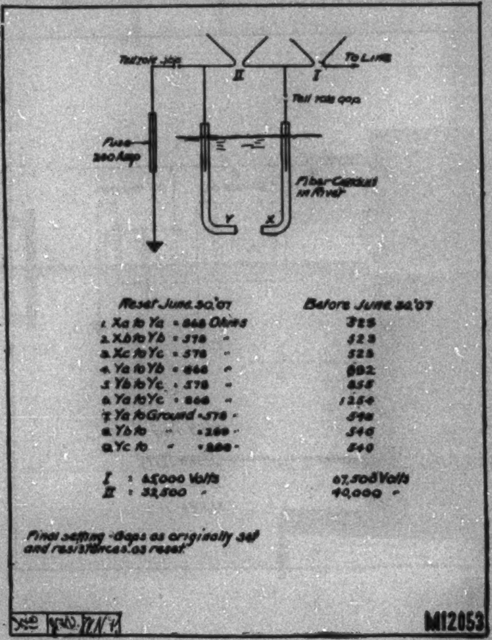
Type *C*. One wire on knobs attached to the pole near the center of the delta (Fig. 12).

Type *D*. Two wires in the same position as in Type *B*, but supported on pipe pins set in the ends of a cross-arm attached near the top of the pole.

In the above constructions the grounded wires were of No. 6

hard-drawn copper. The ground connections were of 0.5 in. by 0.0625 in. galvanized iron ribbon wire at every fourth pole and the ground made by 0.75 in. galvanized iron pipe driven to moist ground.

*Lightning-rods.* Four types were used, erected in the nine-mile zone in sections from one to two miles long, separated by unprotected sections as in the case of the grounded wire constructions as follows:



| Reset June 30,'07 | Before June 30,'07 |
|---|---|
| 1. Xa to Ya = 868 Ohms | 325 |
| 2. Xb to Yb = 578 " | 523 |
| 3. Xc to Yc = 578 " | 523 |
| 4. Ya to Yb = 868 " | 892 |
| 5. Yb to Yc = 578 " | 855 |
| 6. Ya to Yc = 868 " | 1254 |
| 7. Ya to Ground = 578 " | 540 |
| 8. Yb to " = 289 " | 540 |
| 9. Yc to " = 289 " | 540 |
| I = 65000 Volts | 67,500 Volts |
| II = 32,500 " | 40,000 " |

Final setting - Gaps as originally set and resistances as reset.

FIG. 5

Type *A*. Rods of 1.25 in. galvanized iron pipe attached to the poles and extended by tridents of copper wire reaching 6 ft. above the top line wire (Fig. 7).

Type *B*. Rods of 1.5 in. galvanized iron pipe mounted on separate poles 20 ft. to one side of the transmission line and topped by tridents of copper wire extending 25 ft. above the top line wire. Rod poles were spaced at the centers of alternate spans (Fig. 7).

Type *C*. Same as Type *B*, but spaced three rods to four spans.

Type *D*. Same as Type *B*, but spaced 1000 ft. apart.

Ground connections were made as on grounded wire construction, but with two grounds for each rod pole, one at the base of the pole and the other 20 ft. or more away, to insure especially wet ground and to increase the discharge area.

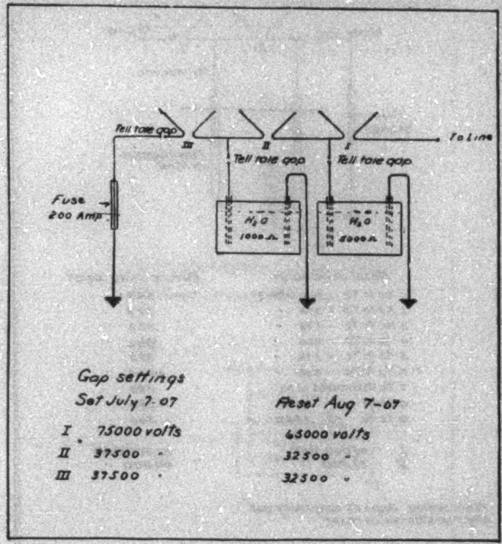

Tell tale gap
III
II
I
To Line
Tell tale gap
Tell tale gap
Fuse
200 Amp
H₂O
1000 Ω
H₂O
5000 Ω
Gap settings
Set July 7-07
I 75000 volts
II 37500 "
III 37500 "
Reset Aug 7-07
65000 volts
32500 "
32500 "

FIG. 6

*Telephone protection*. Each permanent and temporary telephone connection was made through a one-to-one repeating coil and discharge gaps to ground set to break down at about 900 volts.*

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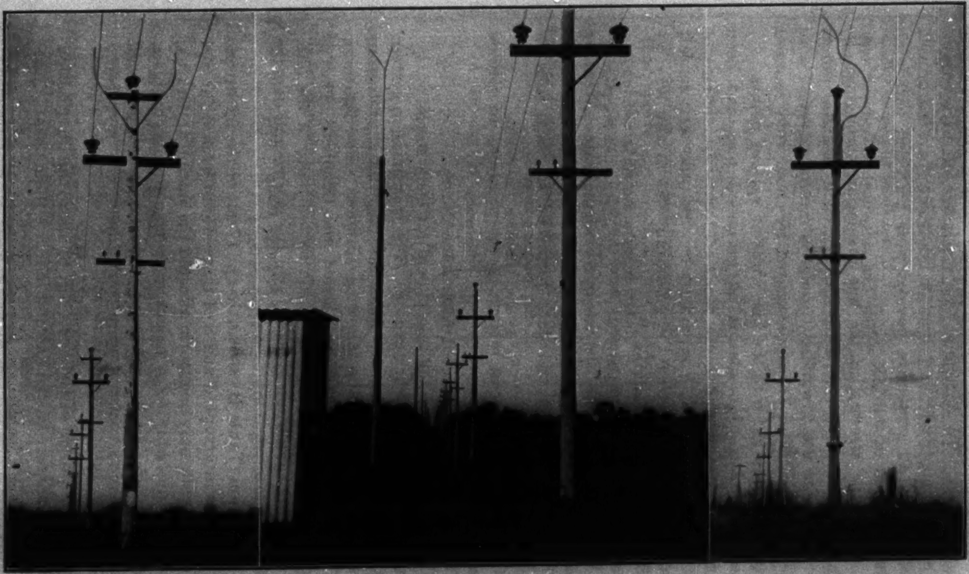
* (American Tel. & Tel. Co. Protection 74-A.)



Overhead grounded wire—type "B"

Lightning-rod—type "B"

Lightning-rod—type "A"

FIG. 7

*Recording devices.* All station arresters were provided with tell-tale papers. To determine the character of disturbances their extent, magnitude, and effect on line and apparatus, ground connections of all protective devices were provided with gaps for the insertion of tell-tale papers.

To study the stresses on the line insulation throughout its length and the behavior of the insulators, each insulator pin at every third pole was grounded through a separate ground wire and tell-tale box (Fig. 7), supplemented by choke-coils shunted with tell-tale gaps cut into the line wires at various points.

After a number of insulators on grounded pins had been damaged, the pin grounds were removed from four sections of about one mile long each, separated by one-mile sections left grounded, to prove whether the grounding was in any way responsible for insulator failures.

*Records.* The following records were kept:

A. Weather conditions shown by United States Weather Bureau reports, and reports of observers along the line.

B. Storm occurrences and data furnished by local men in charge.

C. Operating and special reports of interruptions to service and damage to system.

D. Tell-tale papers collected after each storm.

E. Graphic analysis of tell-tale papers for each storm.

*Operation and results of first season.* The transmission system was started up in December, 1906, and lightning protection records carried through the following summer. The lightning season opened late in March and lasted into October. Thirty-two storms occurred during this season within reach of the line.

The following tabulation gives data on the storms and damage to system, or interruptions to service.

The tabulation (Table B shows that in 17 out of the 32 storms the service was interrupted and 8 of these storms caused damage to insulators, while only one storm affected the station apparatus; this was due probably to a defect in a transformer bushing, but was not sufficient to interrupt the service. Out of 42 insulators damaged, only 3 were punctured, the rest being shattered.

The plan and profile of the line (Fig. 8) show the distribution of damaged insulators on the line and indicate their phases, location on pole or tower, etc.

The following tabulation (Table A) further analyzes insulator damage.

### TABLE A.

### Analysis of Insulator Failures

| | | |
|---|---|---|
| Total number of storms | 32 | |
| Number damaging insulators | 8 | |
| Total number of insulators on line, approximately | 5,500 | |
| Number damaged | 42 | 0.8% of total damaged |
| " shattered | 39 | 92.9% " " " |
| " punctured | 3 | 7.1% " " " |
| " top insulators | 23 | 54.7% " " " |
| " on west side | 6 | 14.3% " " " |
| " " east " | 13 | 31.0% " " " |
| " " brace " | 12 | 28.6% " " " |
| " " opposite side | 5 | 11.9% " " " |
| Total number insulators on grounded pins, approx | 1,650 | 30.0% " " |
| Total number insulators on ungrounded pins, approx | 3,850 | 70.0% " " |
| Number damaged on grounded pins and towers | 35 | 83.3% " " damaged |
| Number damaged on towers | 3 | 7.2% " " " |
| " " on ungrounded pins | 7 | 16.7% " " " |
| " " in sections where grounds had been removed | 4 | 9.5% " " " |
| " " on more or less exposed heights | 28 | 66.7% " " " |
| " " in wet bottoms | 8 | 19.0% " " " |
| " " scattering | 6 | 14.3% " " " |
| Number damaged under overhead grounded wires. (At or near ends only) | 2 | 4.8% " " " |
| Number damaged under lightning rods on poles | 3 | 7.2% " " " |
| " " under lightning rods on separate poles | 0 | 0.0% " " " |
| *Poles split.* | | |
| Number with pin grounds | 0 | |
| Number without pin grounds | 1 | |
| *Poles burned.* | | |
| Number with pin grounds | 2 | |
| Number without pin grounds | 0 | |

The chief operating troubles were interruptions due to short-circuits and grounds from spilling over of insulators, generally accompanied by permanent damage to a part of such insulators (Figs. 9 and 10). Another serious cause of interruption during the latter part of the season was due to too low a setting of the horn arrester at the power house; this did not appear with the higher setting earlier in the season.

## TABLE B.

### DATA ON STORMS AND DAMAGE TO SYSTEM

| Characteristics of Storms | | | | | | | | | | | | Damage. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Time | Location | Direction | Lightning | In. of rain | Wind Max. m.p.h. | Pole No. | Ph. | Loc. | Pin | Brace | Insulation damage | Duration of interruptions | Remarks |
| 3/23 | 11:20–11:50 a.m | Dist. | | Little | 0.03 | 24 | | | | | | | | |
| 5/12–13 | 9 p.m.–6 a.m. | " | | Heavy | 0.10 | 32 | 1532 | C | Top | Gr. | — | * | None | Sub-A transformer bushing punctured. Telephone not disturbed. |
| 6/9 | 3–6 a.m. | Near sub-A | | " | 0.10 | 40 | | | | | | | " | |
| 6/9 | 5 p.m. | | | 1-flash | 1.20 | — | | | | | | | " | |
| 6/15 | 8–10 a.m. | | | Frequent | 0.30 | 44 | | | | | | | " | |
| 6/16 | 5 p.m. | Dist. to NW | | | T | 32 | | | | | | | " | |
| 6/21 | 5:30–8:30 p.m. | | W. to E. | Heavy | 0.55 | 27 | | | | | | | | |
| 6/22–3 | 9:30 p.m.–1 a.m. | | | " | 0.16 | 30 | 1571 | A | W-side | Gr. | Br. | * | 18 hrs. | Pole 1571 burned by wire, dropping from broken insulator. Line interrupted by switching following trouble. |
| 6/23 | 12–1 p.m. | | | Mild | 0.0 | | | | | | | | None | |
| 6/24 | 5 p.m. | Dist. to E. | | | 0.0 | 16 | | | | | | | " | |
| 6/29 | 6 a.m. | | | Heavy | 0.0 | 17 | 1474 | B | W-side | Gr. | None | ★ | | Insulators replaced Sunday July 1, when line shut down for repairs. |
| | | | | | | | 1478 | " | E- " | " | Br. | ★ | | |
| 6/30 | 12–8 a.m. | 5 mi. from p.h. bet. poles 172–288. | | " | 0.03 | 23 | 193 | A | Top | " | None | * | Line held for 1 hour after damage; then out 30 hours for repairs. | |
| | | | | | | | Tr 224 | " | " | " | — | * | | |
| | | | | | | | 267 | " | " | " | — | * | | |
| | | | | | | | Tr 288 | " | " | " | — | * | | |
| | | | | | | | 193 | B | W-side | " | — | * | | |
| | | | | | | | 172 | C | E-side | " | Br. | * | | |
| | | | | | | | 208 | " | " - " | " | " | * | | |
| | | | | | | | Tr 224 | " | " - " | " | " | * | | |
| 7/4 | 10:30–12:30 p.m. | 2 mi. east of Hugo. | W. to E. | Heavy | 0.16 | 38 | 918 | A | E- " | " | " | * | | Power not on line during day. |
| | | | | | | | 934 | " | Top | " | — | * | | |
| | | | | | | | 937 | " | " | " | — | * | | |
| | | | | | | | 909 | B | " | " | — | * | | |
| | | | | | | | 912 | " | " | " | — | * | | |
| | | | | | | | 915 | " | " | " | — | * | | |
| | | | | | | | 918 | C | W-side | " | None | * | | Pole 918 burned by lightning. |
| | | | | | | | 931 | " | E- " | " | Br. | * | | |
| 7/13 | 9:30–11 p.m. | | | Heavy | 0.36 | 53 | | | | | | | | |
| 7/14–15 | 8:30 p.m.–1 a.m. | Near p.h. | | " | 2.76 | 20 | 60 | B | Top | " | — | * | 12 hrs. | Telephone not disturbed. |
| | | | | | | | 72 | " | " | " | — | * | | |
| 7/19 | 1 a.m. | Dist. to E. | | | 0.36 | 20 | | | | | | | | |
| 8/1 | 1:30–2 a.m. | Dist. to W. | | | 0.22 | 46 | | | | | | | | |
| 8/4 | 5:30–7:30 p.m. | Dist. | | | 1.39 | 27 | | | | | | | | |
| 8/6 | 2 a.m. | Dist. | | | 0.0 | 21 | | | | | | | | |

| Date | time | Location | Direction | Lightning | In. of rain | Wind max. m.p.h. | Pole | Ph. | Loc. | Pin | Brace. | Insulation damage | Duration of interruption | Remarks. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8/6 | 1:30–3 p.m. | | | Heavy | 0.04 | | 1028 | A | Top | Gr. | — | ★ | 25 hrs. | |
| | | | | | | | 1065 | " | " | Not | — | ✱ | | Lightningrodonpole |
| | | | | | | | 1067 | " | " | Gr. | — | ✱ | | " " " " |
| | | | | | | | 1070 | " | " | " | — | ✱ | | |
| | | | | | | | 1150 | B | E-side | " | Br. | ✱ | | |
| | | | | | | | 1111 | C | Top | " | — | ✱ | | |
| | | | | | | | 1135 | " | " | " | — | ✱ | | |
| | | | | | | | 1138 | " | " | " | — | ✱ | | |
| | | | | | | | 1141 | " | " | " | — | ✱ | | |
| | | | | | | | 1144 | " | " | " | — | ✱ | | |
| 8/8 | 12:30–1:30 a.m. | Dist. | | | 0.16 | 24 | | | | | | | None | |
| 8/15 | 6:30–8 p.m. | Minneapolis to p.h. | Parallel to line | Heavy | 0.76 | 40 | | | | | | | " | Heavy line disturbances. |
| 8/18 | 7:30–12 p.m. | Minneapolis to p.h. | Parallel to line | Very hvy. | 2.26 | 62 | 1332 | A | E-side | Gr. | Br. | ✱ | 20 hrs. | |
| | | | | | | | 1335 | " | " | " | " | ✱ | | |
| | | | | | | | 1341 | " | " " | " | " | ✱ | | |
| | | | | | | | 1355 | " | Top | Not | — | ✱ | | |
| | | | | | | | 1357 | " | " | " | — | ✱ | | Pole split. |
| | | | | | | | 1351 | B | W-side | " | Br. | ✱ | | |
| | | | | | | | 1357 | " | " " | " | None | ✱ | | |
| | | | | | | | 1350 | C | E-side | " | Br. | ✱ | | |
| | | | | | | | 1351 | " | " " | " | None | ✱ | | |
| | | | | | | | 1387 | " | " " | Gr. | — | ✱ | | |
| 9/6 | 7:30–9 p.m. | E. of Minn. | | Heavy | 0.16 | 25 | | | | | | | None | |
| 9/15 | 4:30–5 p.m. and 7–8 p.m. | | | " | 0.32 | 19 | | | | | | | P. h. breaker opened by horns | Between Sept. 15 and 23 breakers at p.h. opened 9 times by operation of p.h. horn arresters which were set at too low a discharge point. |
| 9/16 | 1:30–2 a.m. | | | " | 0.38 | 25 | | | | | | | | |
| 9/17 | 3:30–4:30 a.m. | | | | 0.22 | 38 | | | | | | | P.h. breaker opened; no horn discharge. | |
| 9/18 | 4–5:30–p.m. | | | | 0.01 | 36 | | | | | | | | |
| 9/19 | 8 p.m. all night | | | | 2.98 | 38 | | | | | | | P.h. breaker opened twice by horn. | |
| 9/22 | 6:30–7:30 p.m. | | | | 0.05 | 28 | | | | | | | P.h. breaker opened by horn | |
| 9/23 | 5:30 p.m. | No storm. | | | | | | | | | | | P.h. breaker opened by horn. | |
| 9/24 | 1:45 a.m. | " " | | | | | | | | | | | 12 hrs. | Line choke coil grounded. |
| 10/1 | 12 m. | Dist. Ltg. | | | 0.63 | 27 | | | | | | | | |
| 10/3 | 4–a.m. | " " | | | 0.15 | 27 | | | | | | | | |

Abbreviations and Symbols.

Ph. = Phase A, B, or C.
Loc = Location on pole.
Br. = Brace side.
P.h. = Power house.
None = Not brace side.
Gr. or Not = Insulator pin grounded or not.
✱ = Insulator shattered.
★ = Insulator punctured.

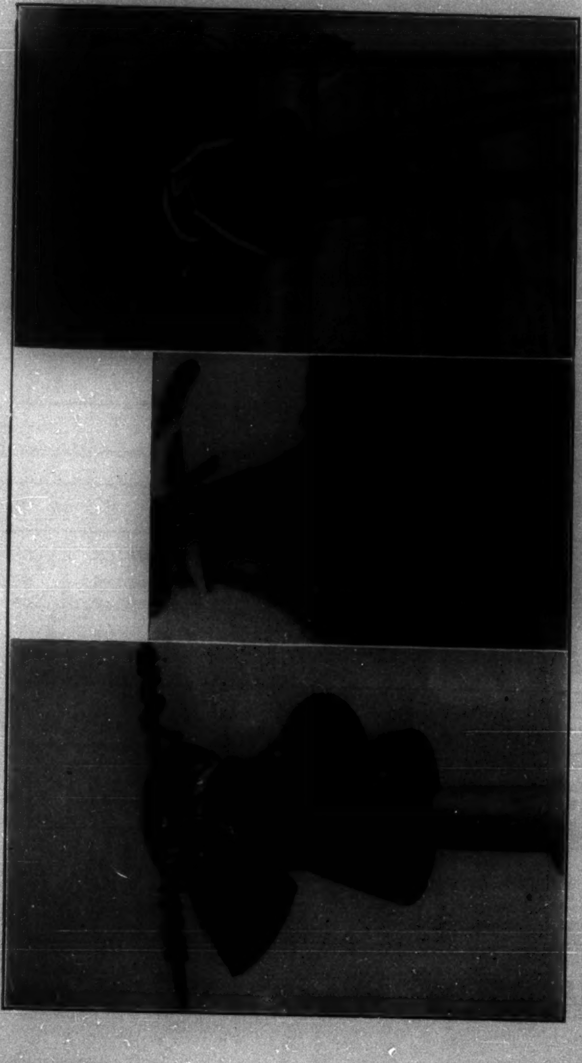


FIG. 9—Damaged insulators

*Graphic records of tell-tale papers.* The graphic records of tell-tale papers show in the form of curves (Figs. 11 and 12 and Appendix) the relative stresses on and discharges over insulators, or through arresters throughout the system, for the full storm series of the season comparing the action of various protective devices storm by storm.

The ordinates of the curves represent the relative size of puncture of tell-tale papers, the scale being so selected as to show as nearly as practicable the relative activity at each point on the line. Curves *A*, *B*, and *C* (Fig. 11) refer to the tell-tale papers placed in the grounds of the insulator pins on the corresponding phases and the fourth curve " Sp ." to the papers in the grounds of the protective devices. The relation of phases and transposition points, locations of special protective devices, choke-coils, pole numbers, etc., are shown at the top of the sheet. The columns to the right refer to the papers in the various types of arresters and give data for each storm. The curves on enlarged chart (Fig. 12) show the sum of the diameters of punctures for the three phases, and the corresponding punctures for the protective device grounds. In the preparation of these charts the tell-tale papers have been interpreted as follows:

Puncture, honeycombing, or discoloration of tell-tale papers, without blistering indicates quiet static discharge or static stress, as from the condenser action of the line and insulators, shown on chart by light line in curves *A*, *B*, and *C* (Fig. 11) and by "*S*" on the arrester records.

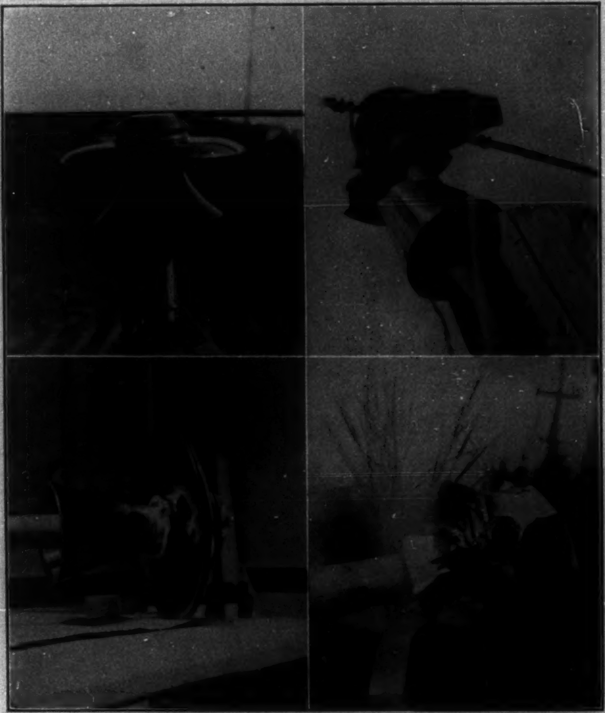
Blistering, that is, bursting apart of laminations of tell-tale papers or tearing of papers, without burning, indicates a disruptive static discharge, shown by heavy line in curves and "*O*" (Fig. 11).

Burning of puncture indicates dynamic current, shown by solid curve and "*O*" (Fig. 11).

## DATA FROM OPERATING REPORTS OF 1907.

*Storm, May* 12–13, 9 *p.m. to* 6 *a.m.* Sub-station transformer bushing grounded. Telephone wires at sub-station burned off. Top insulator pole 1532 Ph. "*C*", 4.5 miles from sub-station shattered, one side of all petticoats being broken. Current leaking to grounded pin slowly burning pole. No interruption until current off for repairs 19 hours later.

*Storm, June* 22–23, 9:30 *p.m. to* 1 *a.m.* Pole 1571 reported burning at 11 p.m. 11:30 to 12 p.m. surges on power house instruments and heavy discharges over static dischargers on low-tension side of transformers, burning out one set of dischargers. Breakers thrown out, then line cleared up. Pole 1571 reported still burning at 12:30, grounded line. Double arms burned off by wire dropping from broken insulator. Pin ground wire across line and telephone wires, making the telephone alive.



Shattered 8/18/07, pole 1341 Punctured 8/7/07, pole 1028
Punctured 6/29/07, pole 1474 Same insulator (pole 1028)
FIG. 10 showing fused puncture

Pole badly burned, necessitating renewal. Telephone in order after clearing wires. When spillover at pole 1571 Ph. "*A*" pin ground fused off. Sub-station cell-type arrester active on Ph. "B" and "C". Low-equivalent arrester inactive. Service interrupted by switching operations after trouble only. Line out for repairs 18 hours.

*Storm, June* 29, 12 *to* 6 *a.m.* Side insulators poles 1474 and 1478 "B" punctured and broken. No interruption until repairs June 30. Telephone out. Station arresters inactive.

*Storm, June* 30, 12 to 8 *a.m.* Top insulators shattered on towers 224, 288, and poles 193 and 267 Ph. "A"; pole 193 Ph. "B"; and tower 224 and poles 172 and 208 Ph. "C"; P.H. horn arrester discharged on Ph. "B", arc breaking in two to three seconds without any disturbance to synchronous apparatus. Short-circuit one hour later.

*Storm, July* 4, 10:30 *a.m. to* 12:30 *p.m.* Current not on line after 4 a.m. Insulators shattered on poles 918, 934, 937, Ph. "A"; 909, 912, 915 Ph. "B"; and 918, 931 Ph. "C". Pole 918 burned off two feet below cross-arm. Pole set on fire by lightning as no line current was on. Line tested and found short-circuited at 1 p.m. Line put in operation 7:25 a.m. July 5. Most of damage on unprotected section between overhead ground wires types "A" and "B".

*Storm, July* 14–15, 8:30 *p.m. to* 1 *a.m.* Near power house. Insulators shattered on poles 60 and 72 Ph. "B" shutting down station for 12 hrs. Power house static dischargers burned somewhat. Power house horn arrester operated once. Telephone not affected.

*Storm, Aug.* 6, 1:30 *to* 3 *p.m.* Nine insulators shattered on poles 1065, 1067, 1070 Ph. "A"; 1150, Ph. "B", 1111, 1135, 1138, 1141, 1144, Ph. "C". Insulator punctured pole 1028, Ph. "A". Fused through all four parts and several minor punctures. Hugo horn arrester slightly active Ph. "A"; others inactive. Cell-type arrester discharged Ph. "A" and "B". Sub-station low-equivalent arresters discharged Ph. "C". Line out 25 hours.

*Storm, August* 18, 7:30 *to* 12 *p.m.* Most severe storm for several years. Lightning practically incessant. Heavy short-circuit on line at 8 p.m.; recovered for few minutes, then permanently out. Pole 1357, from which ground wires had been removed, split from top to below cross-arm where guy was attached. Top insulator shattered. Nine other insulators shattered on poles 1332, 1335, 1341, 1355, 1357, Ph. " A ": 1350, 1351, 1357, Ph. " B "; and 1351, 1387, Ph. " C ". Six of these were in sections where pin grounds had been removed. No evidence of short-circuits on any poles. Papers in line choke-coils on pole 1356 burned up and cylinders burned. Choke-coil on 1615 Ph. " A " paper blistered. Beside spillovers between 1300 and 1400, several between 800 and 950, but without damage. Other spillovers on 300, 353, 408, 563, 1034, and 1254 without damage.

*Storms, September* 15–42. Several of these were severe. Transmission line put out of service 9 times in 9 days. Six of these caused by power house horn arrester discharging, opening breakers. Arc held on horn tips, and in one case followed up lead toward tower, drawing an arc 20 to 30 ft. long. Probable cause, wind. Action of horns much more severe than with wider setting during earlier part of season. No damage from lightning.

## ANALYSIS OF RECORDS

Examination of the plan and profile (Fig. 8) indicates that:

Points where the line was especially liable to damage are, first, exposed heights and, next, wet bottom lands.

Damage was usually concentrated within a distance of a mile or two, with the exception of the two storms of June 30 and August 6, in the latter of which the storm crossed the line at a slight angle; and in the former, although there is no record of the direction of travel of the storm, there are indications that it traveled along the line for some distance.

Thus far, trouble has not been confined to any defined points on the line, but as yet there is insufficient conclusive evidence on this point.

The tabulation of line failures appears to show that:

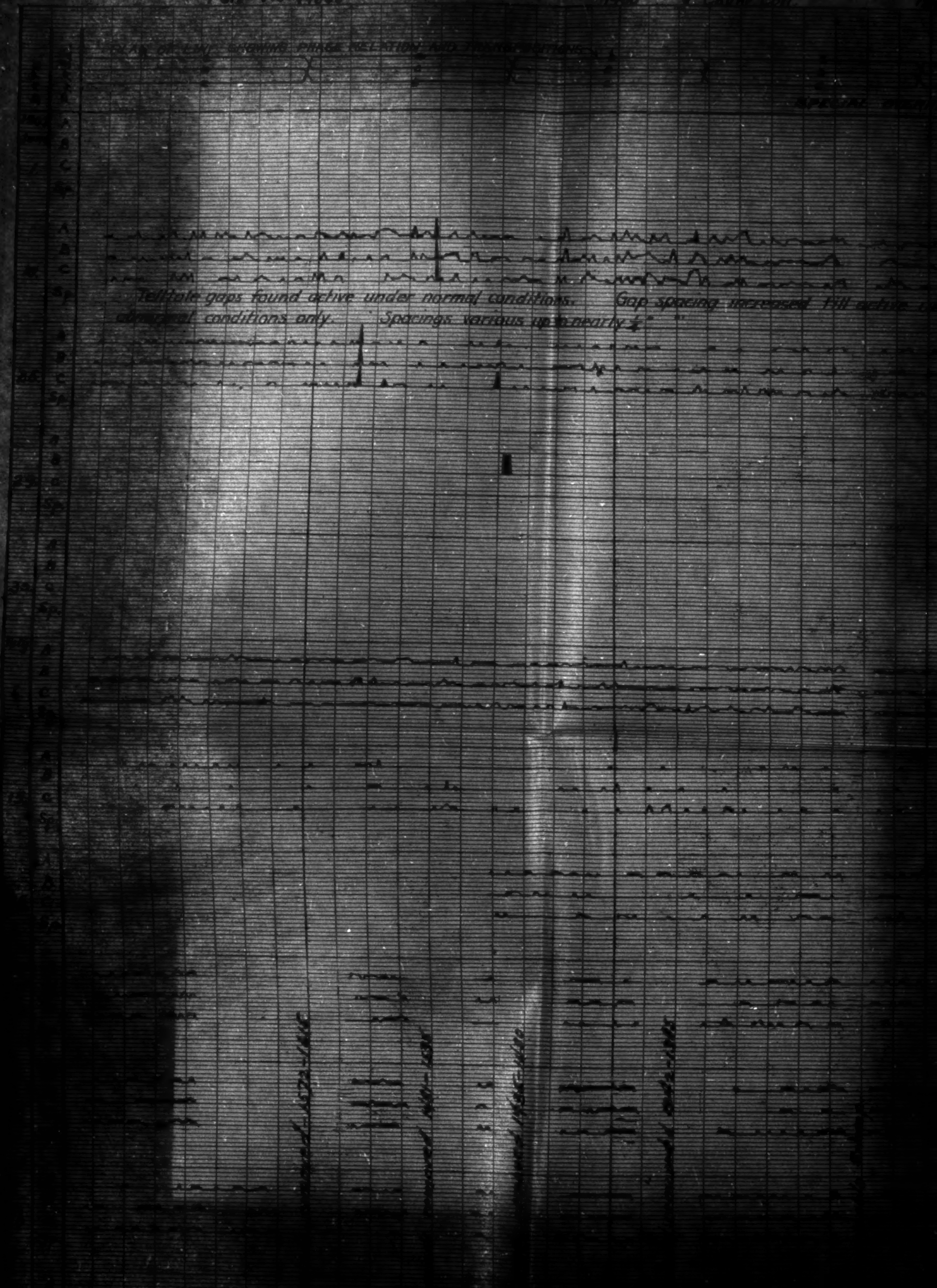
Where grounded and ungrounded pins came on adjacent poles, damage to the insulators generally occurred at the grounded pin, but the damage of a group of insulators on a section of line where all grounds had been removed and on pole 1065 indicates that grounding the pins probably did not materially increase the danger of damage.

Top insulators are somewhat more liable to damage than those on the sides and those on the brace side are apparently somewhat more affected than those on the opposite side.

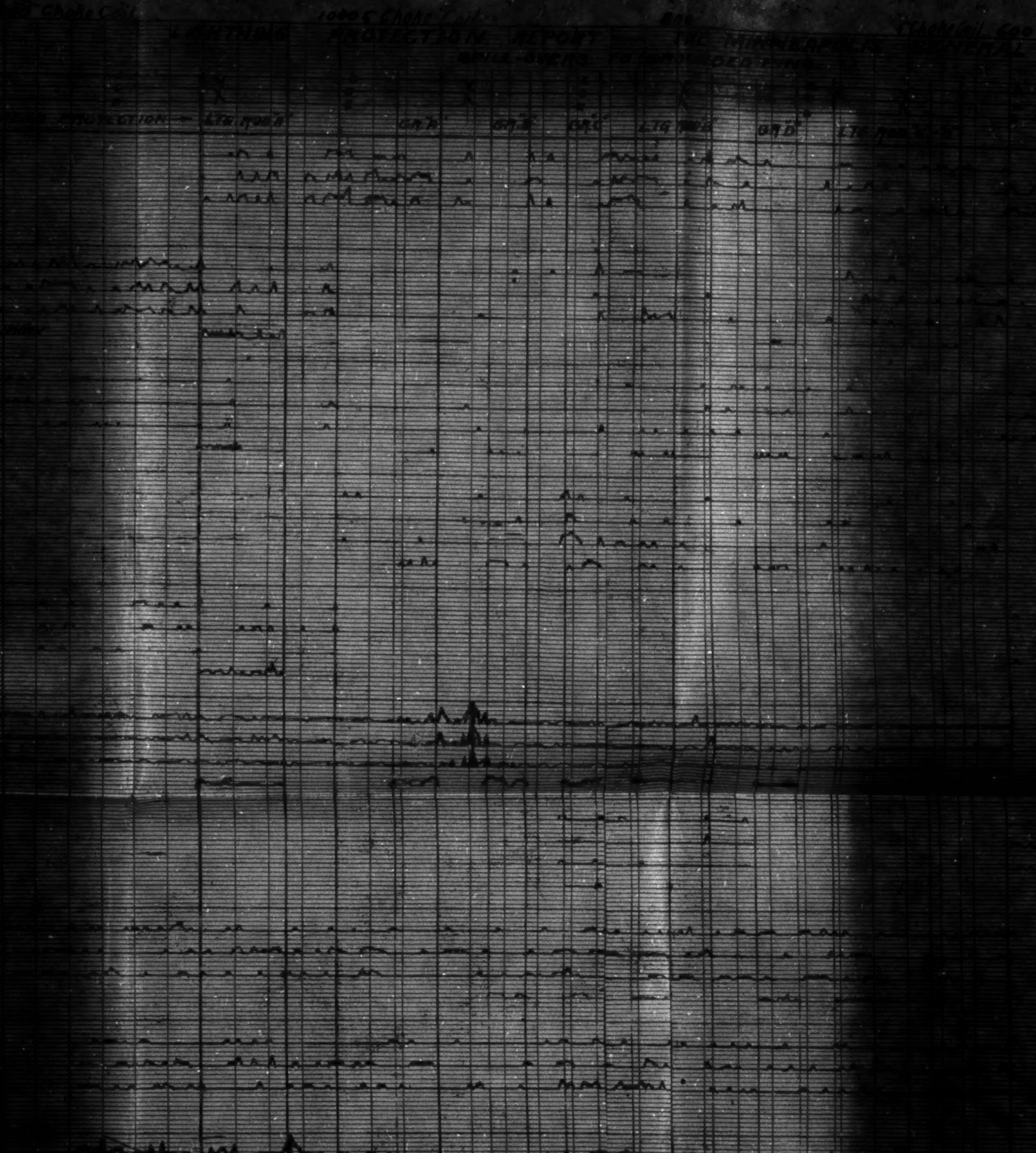
Overhead grounded wire construction materially protects

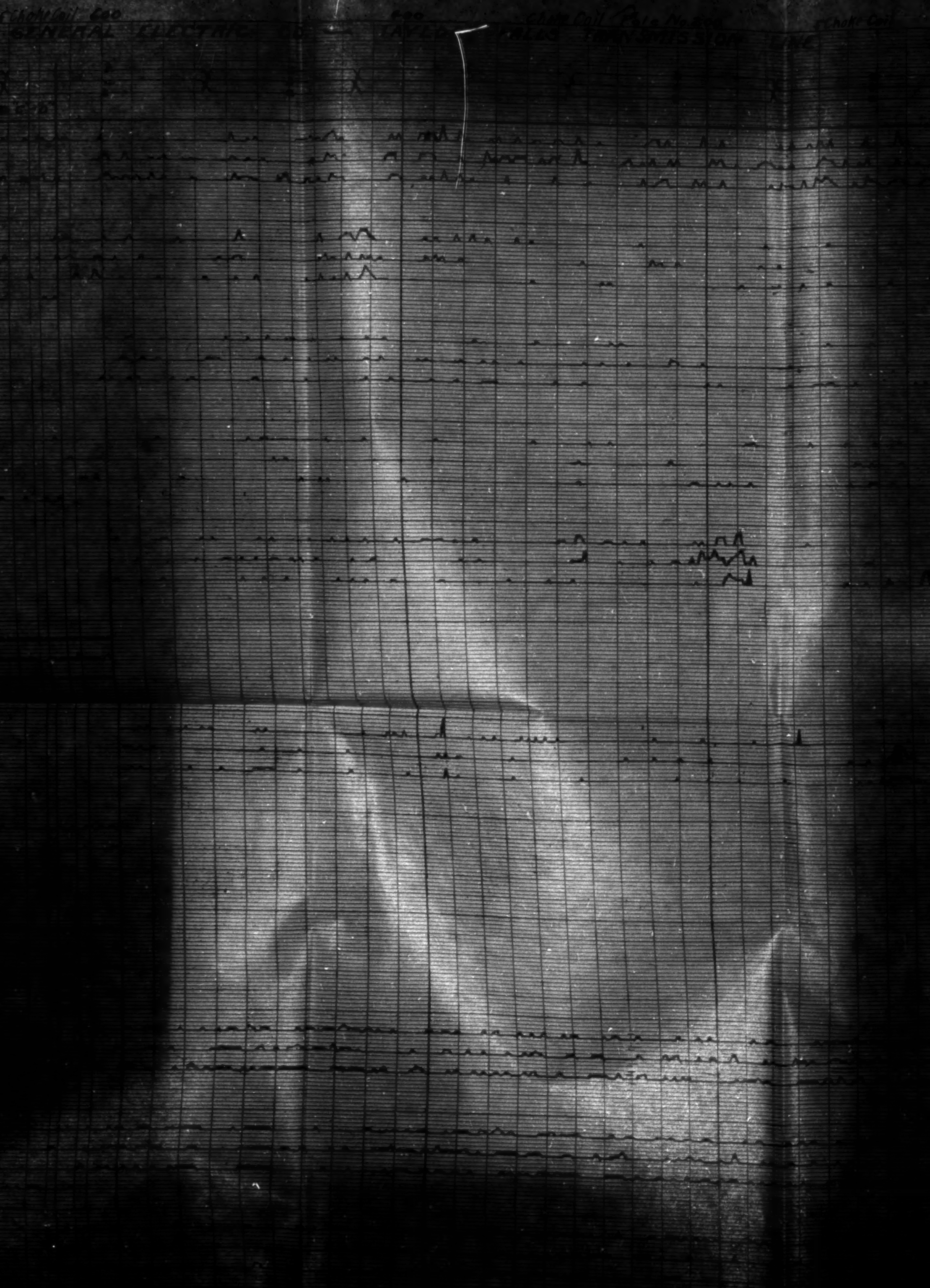
Pole No. { Choke Coil
1899

1900 { Choke Coil



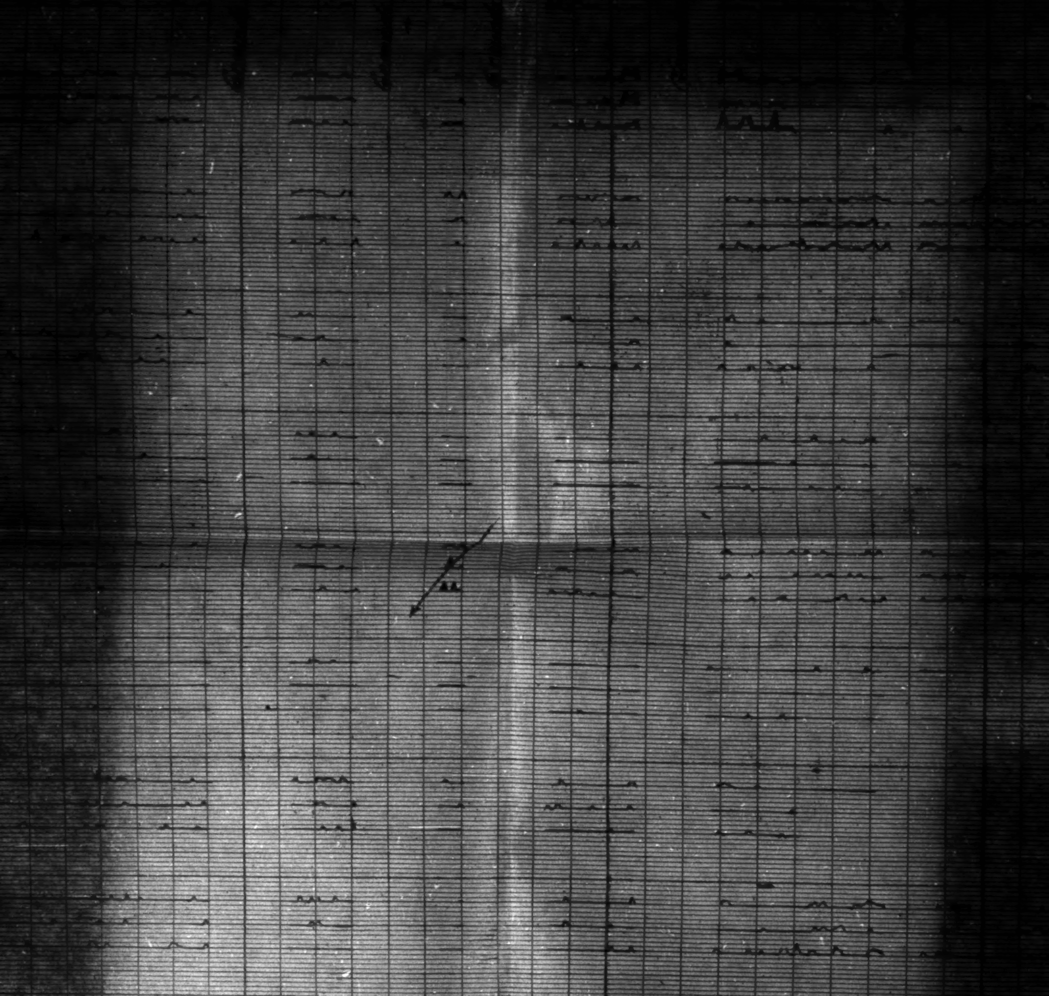
Telltale gaps found active under normal conditions. Gap spacing increased. Still active at abnormal conditions only. Spacings various up to nearly 1/4"


Choke Coil
1000 C Choke Coil
800
C Choke Coil 600
LIGHTNING PROTECTION REPORT
THE MINNEAPOLIS GENERAL
SPILL-OVERS TO GROUNDED WIRE
PROTECTION → LTG ROD A
GR A
GR B
GR C
LTG ROD
GR D
LTG ROD
General Direction of Storm


Choke Coil 600
600
Choke Coil Pole No 8[illegible]
Choke Coil
GENERAL ELECTRIC CO — TAYLOR FALLS TRANSMISSION LINE

Leg numbers not indicated on telltale papers.

| | |
|---|---|
| Mar 23, 1907. 11:20 to 11:50 A.M. | A few |
| May 12, 1907. 9 P.M. to 6 A.M. | High<br>Insula<br>down.<br>2-30 |
| June 9, 1907. 3-6 A.M. | Quite |
| June 9, 1907. 5 P.M. | Single |
| June 15, 1907. 8-10 A.M. | Frequent |
| June 16, 1907. 5 P.M. | Distant<br>winds. |
| June 21, 1907. 5:30 to 8:30 P.M. | Heavy |
| June 22, 1907. 9:30 P.M. to 1 A.M. | Insula<br>broken.<br>are |
| June 23, 1907. 12-1 P.M. | Small<br>lightning. |
| June 24, 1907. 5 P.M. | Distant |
| June 29, 1907. 12-6 A.M. | Two in |
| June 30, 1907. 12-8 A.M. | Heavy<br>224, 2 |
| | Horn<br>5.1" gap |
| July 4, 1907. 10-30 to 12-30 noon<br>(No current on line) | Severe<br>at time<br>Phase |
| July 13, 1907. 9-30 to 11 P.M. | Severe |
| July 14, 1907. 8-30 to 1 A.M.<br>Papers were punctured<br>both on 13th. & 14th. | Severe<br>on Phase<br>July 7 |
| July 19, 1907. 1 A.M. | Short |
| Aug. 1, 1907. 1:30 to 2 A.M. | Distant |
| Aug. 4, 1907. 5:30 to 7:30 P.M. | Distant |
| Aug. 6, 1907. 2 A.M. | Distant |
| Aug. 6, 1907. 1:30 to 3 P.M. | Severe<br>Phase<br>Phase |
| Aug. 8, 1907. 12:30 to 4:30 A.M. | Quite |
| Aug. 15, 1907. 6:30 to 8 P.M. | Heavy<br>No |

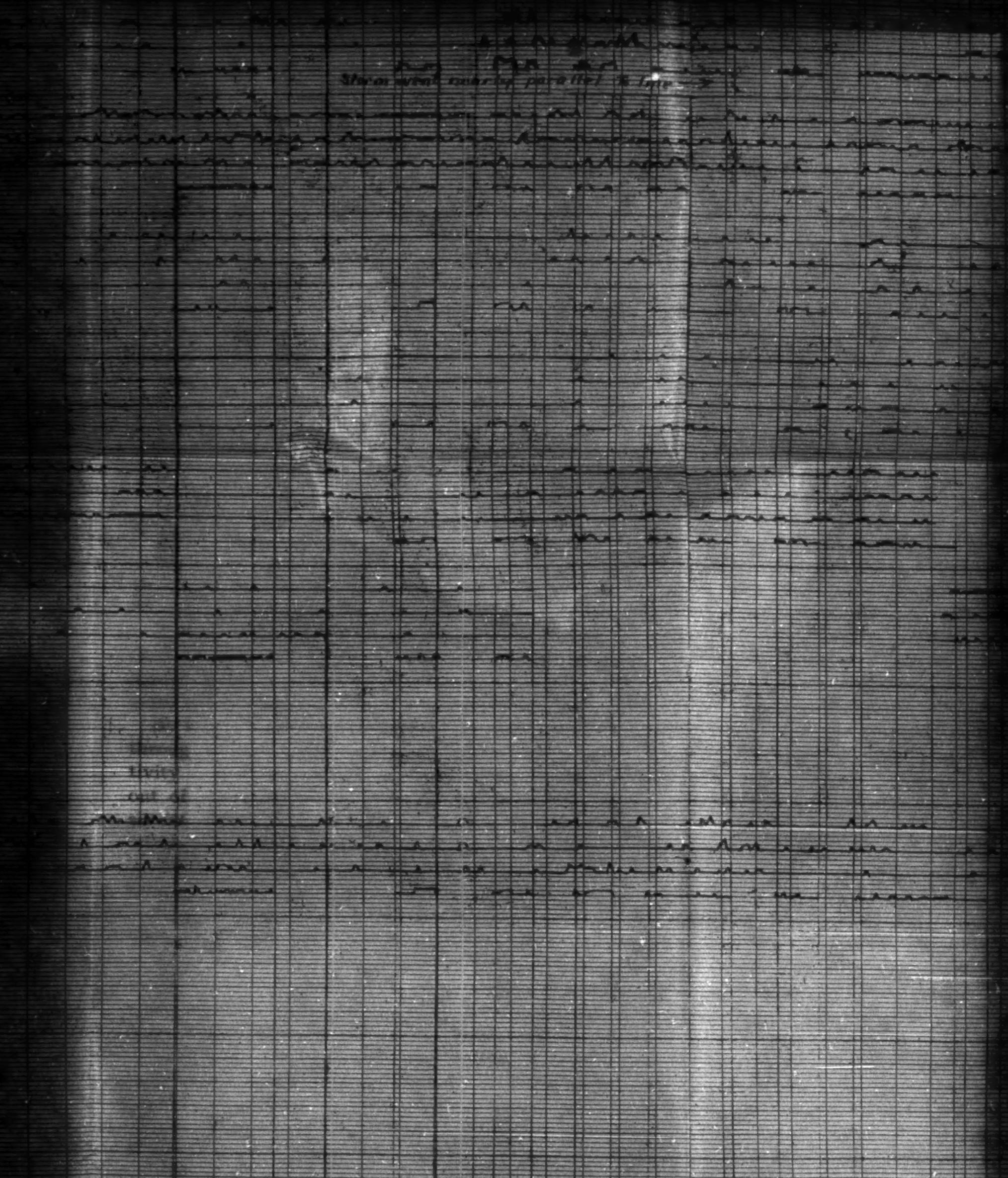


## LEGEND

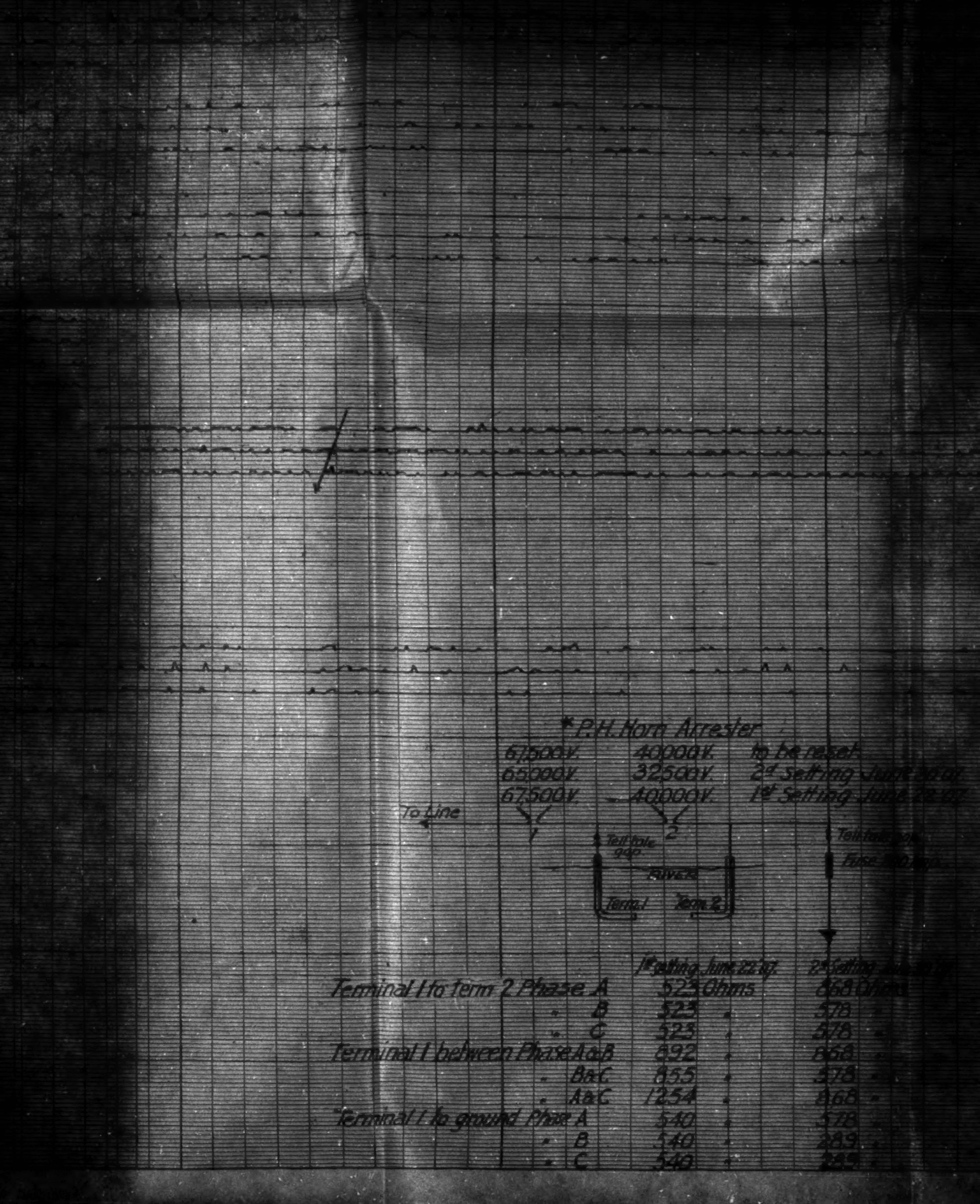
- ⌃⌃⌃ or s - puncture indicating quiet dischar
- ▲▲ or o - blistering indicating disruptive dischar
- ▲▲ or ● - dynamic burning.
- — - telltale paper in but not punctured.

Ordinates represent diameter of holes in telltale papers as follow

5 divisions - total destruction of paper
4½ " " 1" to total destruction
4 " " ½" to 1"
3½ " " 3/8" to ½"
3 " " ¼" to 3/8"
2½ " " 3/16" to ¼"
2 " " 1/8" to 3/16"
1½ " " 1/16" to 1/8"
1 [illegible]

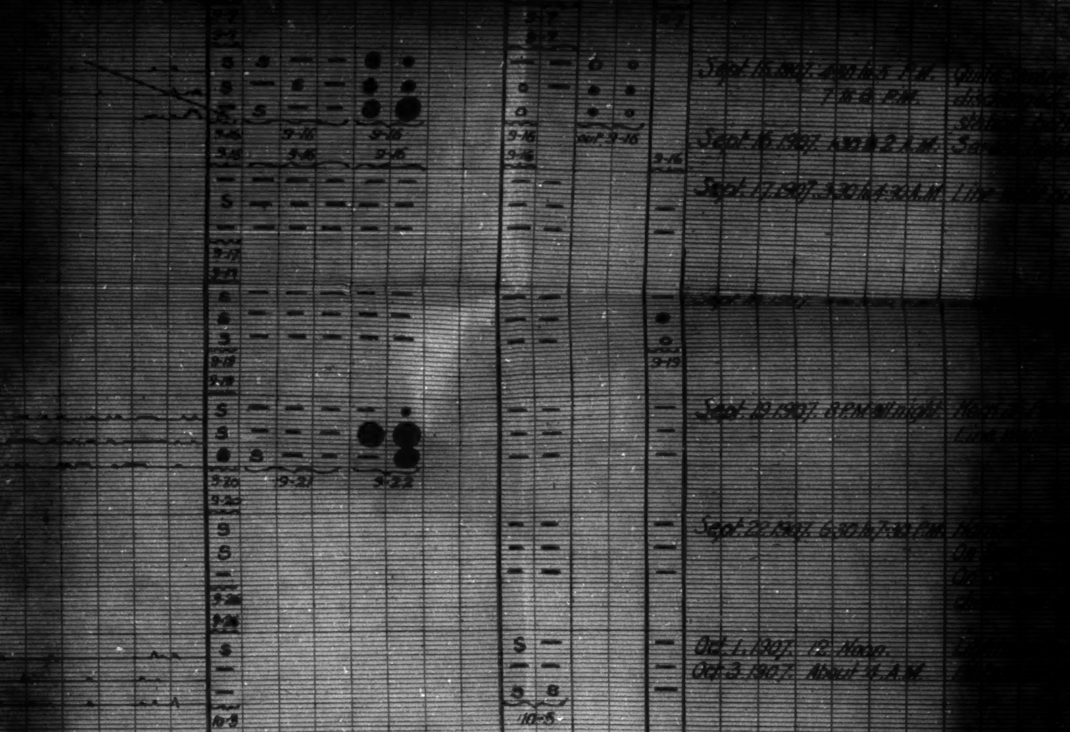


Strong wind nearly parallel to line →



| | 1st Setting June 22 '07 | 2d Setting June 30 '07 |
|---|---|---|
| Terminal 1 to term 2 Phase A | 523 Ohms | 868 Ohms |
| " B | 523 " | 578 " |
| " C | 523 " | 578 " |
| Terminal 1 between Phase A & B | 892 " | 868 " |
| " B & C | 855 " | 578 " |
| " A & C | 1254 " | 868 " |
| Terminal 1 to ground Phase A | 540 " | 578 " |
| " B | 540 " | 289 " |
| " C | 540 " | 289 " |

[illegible] graphic record of tell-tale papers. (Vaughan)



Sept. 15. 1907. 4.00 to 5 P.M.
7 to 8 P.M.

Sept. 16. 1907. 1.30 to 2 A.M.

Sept. 17. 1907. 3.30 to 4.30 A.M.

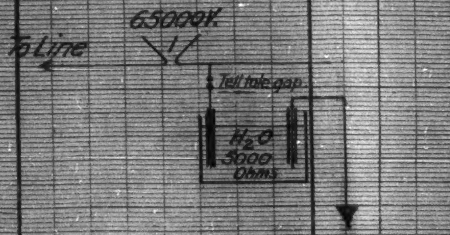
Sept. 18. 1907.

Sept. 19. 1907. 8 P.M. to Midnight.

Sept. 22. 1907. 6.30 to 7.30 P.M.

Oct. 1. 1907. 12. Noon.
Oct. 3. 1907. About 4. A.M.

† Sub. A. Horn Arrester connected in July 3, 1907


65000 V.
To Line
Tell tale gap.
$H_2O$
5000
Ohms

65000 V.
75000 V.
To Line

insulators. The lightning-rods do not seem to have much effect except in cases of direct stroke.

The one case of pole splitting was a pole with no ground connection.

Examination of the tell-tale papers and graphic charts (Appendix and Fig. 11) indicates that:

Storms follow no well-defined paths, nor are their effects confined to any particular part of the line.

Stresses do not occur at any definite points.

Principal disturbances are due to immense static charges on the line in the immediate vicinity of storms. These charges are of great intensity and concentration, frequently spilling over a number of insulators without traveling along the line more than a few hundred feet.

The disturbances are confined to areas extending from one-half to two miles along the line, excepting where storms are traveling parallel to the line, as in the storm of August 18, which suggests recurrent and decreasing activity as the storm passes down the line. Even in this case no area of disturbance was over three miles in length.

In general, the protected nine-mile zone shows an appreciable decrease of insulator stress, activity of devices for distant storms and a very decided shielding effect of overhead grounded wires as well.

By following the curves for each type of grounded wire down through the season on the large graphic chart, Fig. 11, the activity of the grounded wires and the corresponding smoothing out of stresses on the insulators appear pronounced and consistent, with the possible exception of the storm of August 18, which was of unusual severity and traveling parallel to the line, so that charges may have been induced on the unprotected lengths of line between the protected sections of sufficient volume to spread out through the protected sections. A study of the enlarged chart, however, shows pronounced shielding effect even for this storm. The shielding action is especially well shown in the plot for the heavy storm of July 4, which occurred when the line was dead. This storm in traveling parallel to the line from southwest to northeast would naturally affect the unprotected sections of the line between the shielded sections. The chart shows how the shielding effect at the west ends of the short protected sections is counteracted by charges evidently coming on to the unprotected line as the storm approaches each protected section and how it prevents the reestablishment of the charge for some distance into the unprotected sections at the opposite ends.

Although more damage was done to the top and east or brace side insulators, in general the stresses appear greater on the west side, which in this case was toward the approach of the storm.

The effectiveness of the various types of overhead grounded wire appears to be in proportion to their theoretical value, the wires well above the line being the best and the wire in the center of the delta the worst. The activity of the lightning-rods, especially those at the side of the line, is marked. In this same storm, one of type " B " rods passed off a discharge which can be accounted for only by discharge between cloud and ground. This is of especial interest, as a lightning flash photographed by one of the inspectors the previous season showed ramifications apparently covering a territory a mile or two in diameter, emphasizing the necessity for some such protection.* This pole may have received a branch of such a direct stroke and in any case shielded the line from any unusual stress at that point.

The station arrester records on the graphic chart show the low-equivalent type of arresters to have operated according to their theoretical design; but whether the volume discharged was sufficient to keep down dangerous potentials is not certain, since in each important case the simultaneous and vigorous operation of the power house horn arrester outside the station indicated that it took the brunt of the discharge. The cell-type arrester was apparently more sensitive and operated more freely than the other types. There is no record, however, to show its action in disposing of abnormally heavy discharges. On the other hand, it appeared to be more sensitive in responding to strains due to a grounded line, and discharged for considerable periods under this condition without damage. The operation of the horn arresters, especially at the power house has been very promising and appears to fulfil their intended function as an emergency device. Their operation has been chiefly when the line was grounded by the failure of an insulator, but there is one case where the power house horn arrester discharged over both gaps in series without any indication of discharge through the water shunt of the second horn; this indicates that it passed off a high-frequency static discharge without allowing the line current to follow. But this single case is not conclusive. There are other cases, however, which show the passage of heavy disruptive discharges which indicate that these types have handled high-frequency disturbances as well as low-frequency surges. From their action so far it is believed that the two and three-gap types of horn arresters will be effective in handling occasional disturbances whether static or dynamic which might otherwise be of too great magnitude for the station arresters to dissipate, and that this can be done with settings which will not interrupt the line nor necessarily disturb synchronous apparatus.

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* See TRANSACTIONS A. I. E. E., Vol. XXV., p. 901 to 926.

The telephone line ordinarily operated quietly, but, although often too noisy to use in case of line trouble, it was, as a rule, kept from damage by the protectors and recovered when the line cleared up. The effectiveness of the protectors was well illustrated during a ground on one phase by the immediate burning out of two instruments not protected, while a protector on the third instrument discharged freely with no damage to the instrument.

## CONCLUSIONS

The results of the Taylors Falls experiments so far indicate that:

The principal trouble is from temporary or permanent breakdown of line insulation by static charges induced in the line by passing storms.

Direct strokes between cloud and ground may occur at any time. Although there were several cases of damage so caused during construction, the first season's operation gives evidence of only one case and that without damage.

The induced charges are highly concentrated, and often of immense volume and intensity, discharging to ground over insulators with a disruptive effect that tends to shatter, but rarely to puncture them, often without line current following. Line current may or may not follow these discharges; if it follows, it may only temporarily ground or short-circuit the line.

Arcs established by insulator spillovers or leakage of charging current through damaged insulators may burn pole structures or further damage insulators and even fuse the line wire.

Such disturbances may occur anwhere on the line, but with a preference for exposed heights and to a less degree to wet lowlands.

There is no evidence of surges other than the direct effects of grounds or short-circuits, nor of stress at any definite points on the line such as from reflected or standing waves.

Top insulators, and to a less extent those on the cross-arm-brace side of the pole, apparently are more liable to damage, although the cases are not sufficiently frequent to be conclusive.

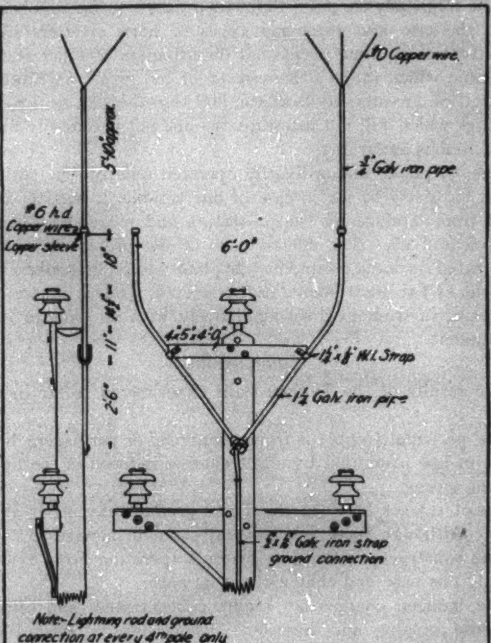
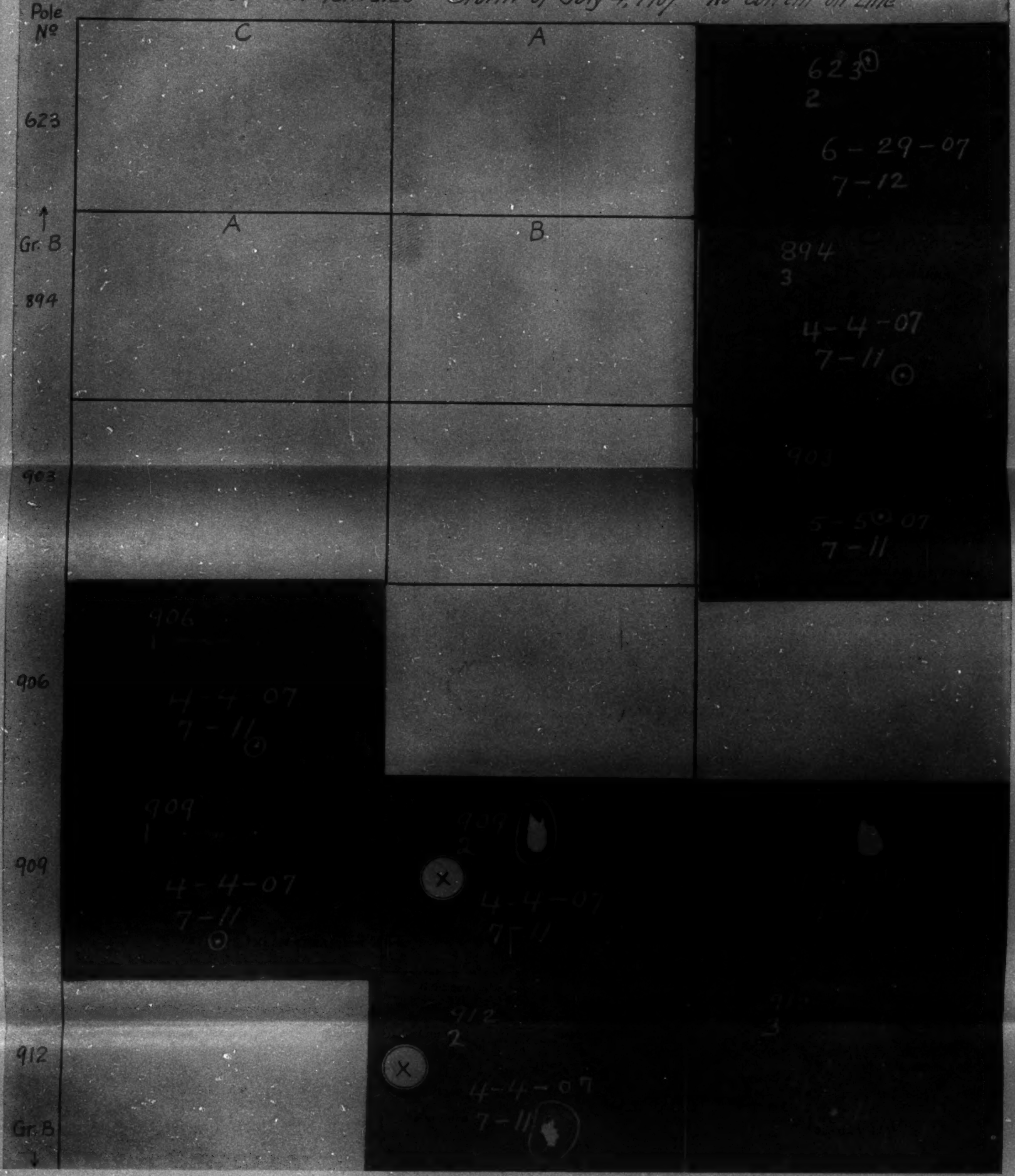

#0 Copper wire.
5'-0" approx.
¾" Galv iron pipe
#6 h.d Copper wire
Copper sleeve
6'-0"
18" - 14½" - 11" - 2'6"
4"x5"x4'-0"
1½"x⅛" W.I. Strap
1½ Galv. iron pipe
2"x⅛" Galv. iron strap ground connection
Note:- Lightning rod and ground connection at every 4th pole only
Scale ½"=1 Ft MARCH 30,1906
M12437

Fig. 13

Grounding of insulator pins by tower structures or otherwise has comparatively little effect in assisting insulator breakdowns.

Overhead grounded wires are of decided value in shielding the

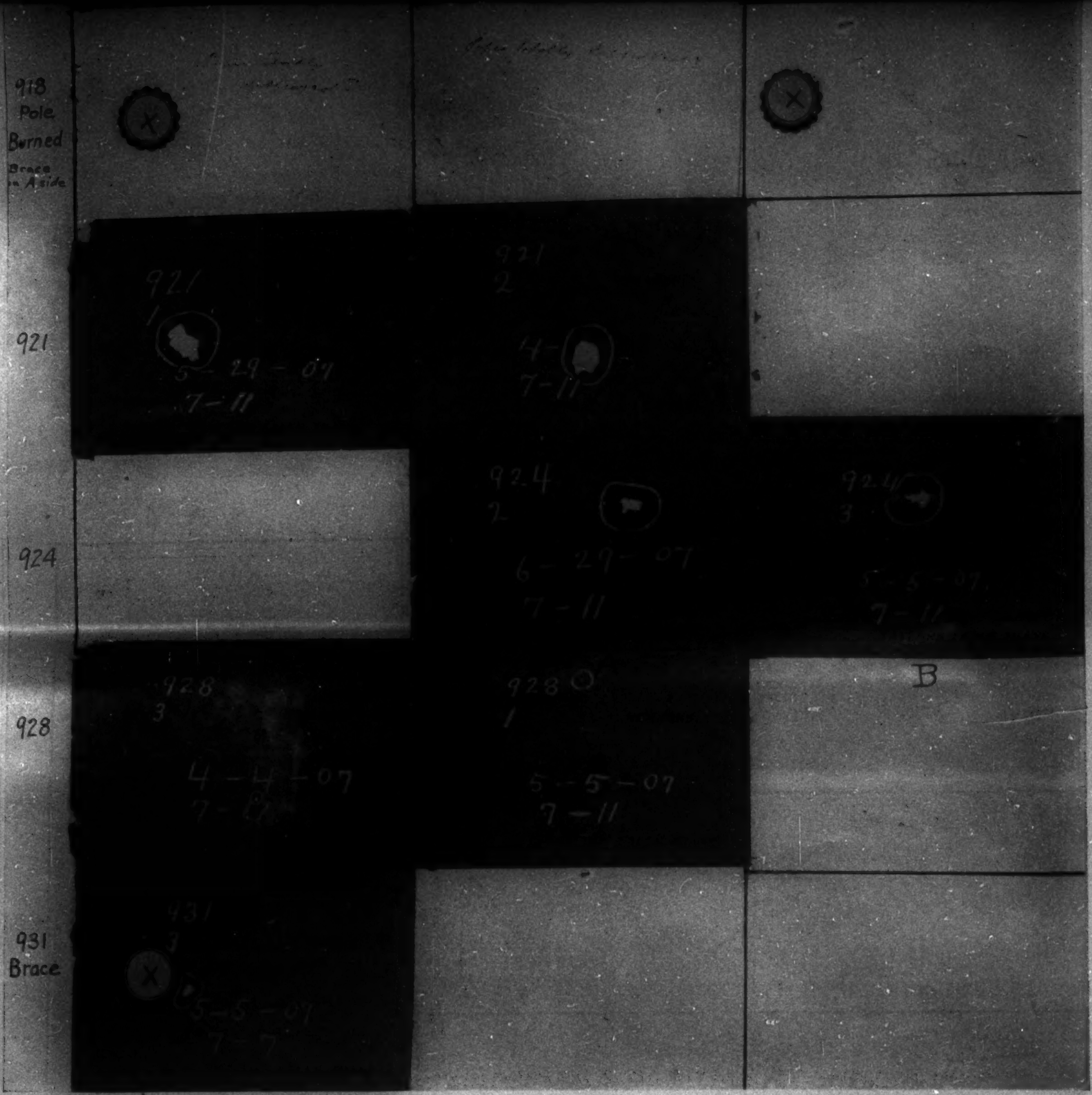
Grounded Pin Telltales    Storm of July 4, 1907    No Current on Line



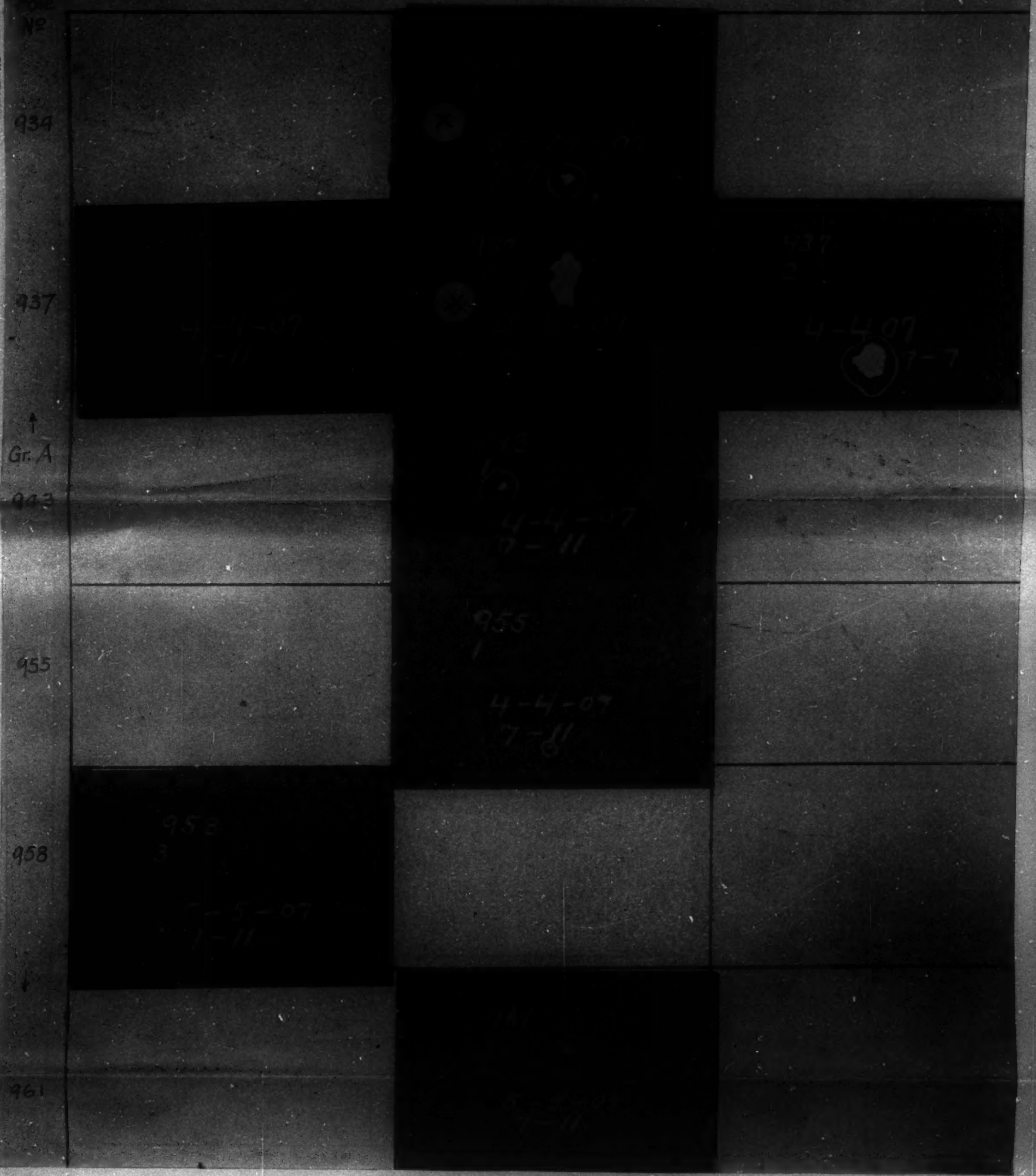
Pole №
623
↑ Gr. B
894
903
906
909
912
Gr. B ↓
C
A
A
B
623
2
6-29-07
7-12
894
3
4-4-07
7-11
903
5-5-07
7-11
906
1
4-4-07
7-11
909
1
4-4-07
7-11
909
2
4-4-07
7-11
912
2
4-4-07
7-11
912
3

Storm of July 4, 1907

Pole No
915
918 Pole Burned Brace on A side
921
924
928
915
1
6-2 -07
7-11
915
2
4-4-07
7-11
915
3
4-4-07
7-11
921
2
7-11
924
2
6-29-07
7-11
924
3
5-5-07
B


918
Pole
Burned
Brace
in Aside
921
921
1
5-29-07
7-11
921
2
4-
7-11
924
924
2
6-29-07
7-11
924
3
5-5-07
7-11
928
928
3
4-4-07
7-8
928
1
5-5-07
7-11
B
931
Brace
931
3
5-5-07
7-7

Storm of July 4, 1907


Pole №
934
937
↑
Gr. A
943
955
958
↓
961
4-4-07
7-11
937
4-4-07
7-7
4-4-07
7-11
955
1
4-4-07
7-11
958
3
-5-07
7-11
7-11

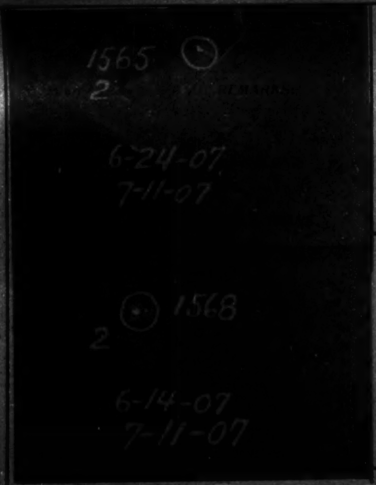
Storm of July 4, 1907

| Pole No |  |  |  |
|---|---|---|---|
| 1129 | B | C | 1129<br>1<br>6-12-07<br>7-12 |
| 1135 |  |  | 1135<br>1<br>4-8-07<br>7-12 |
| 1351 | 1351<br>3<br>6-25-07<br>7-12-07 | A | B |
| 1432 | 1432<br>3<br>6-24-07<br>7-12-07 |  |  |
| 1436 |  |  |  |
| 1556 | 1556<br>2<br>6-24-07<br>7-11-07 | C | A |

Storm of July 4, 1907

Pole No

1565

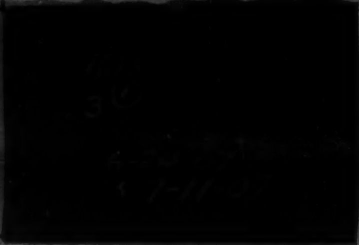

1565
2
REMARKS
6-24-07
7-11-07
1568
2
6-14-07
7-11-07

1568

A

B

1615



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Storm of July, 4, 1907

| 1615 | A | B |
|---|---|---|

Storm of July, 4, 1907

Ltg. Rod. A (B) C D

Pole 820-1 REMARKS:

Date in 6-29 07

Date out 7-11

TAYLORS FALLS TRANS.

Overhead. A B (C) D

Pole 847 REMARKS: [illegible]

Date in 6-29-07

Date out 7-11

TAYLORS FALLS TRANS.

Date in 6-29

TAYLORS

X

Storm of July 4. 1907

Line P.I.
Leg. C
Station St Croix
Date in 6/30-07
" out 7-6-07

Line 50000
Leg. 3 Top
Station Sub A
Date in 6/23/07
" out 7/6-07
REMARKS (see over)
SERIES

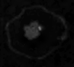
Line Lum
Leg. 1
Station Sub A
Date in 6/20/07
" out 7/6-07
REMARKS (see over)
SERIES

Grounded Pin Telltales Storm of Aug 18, 1907

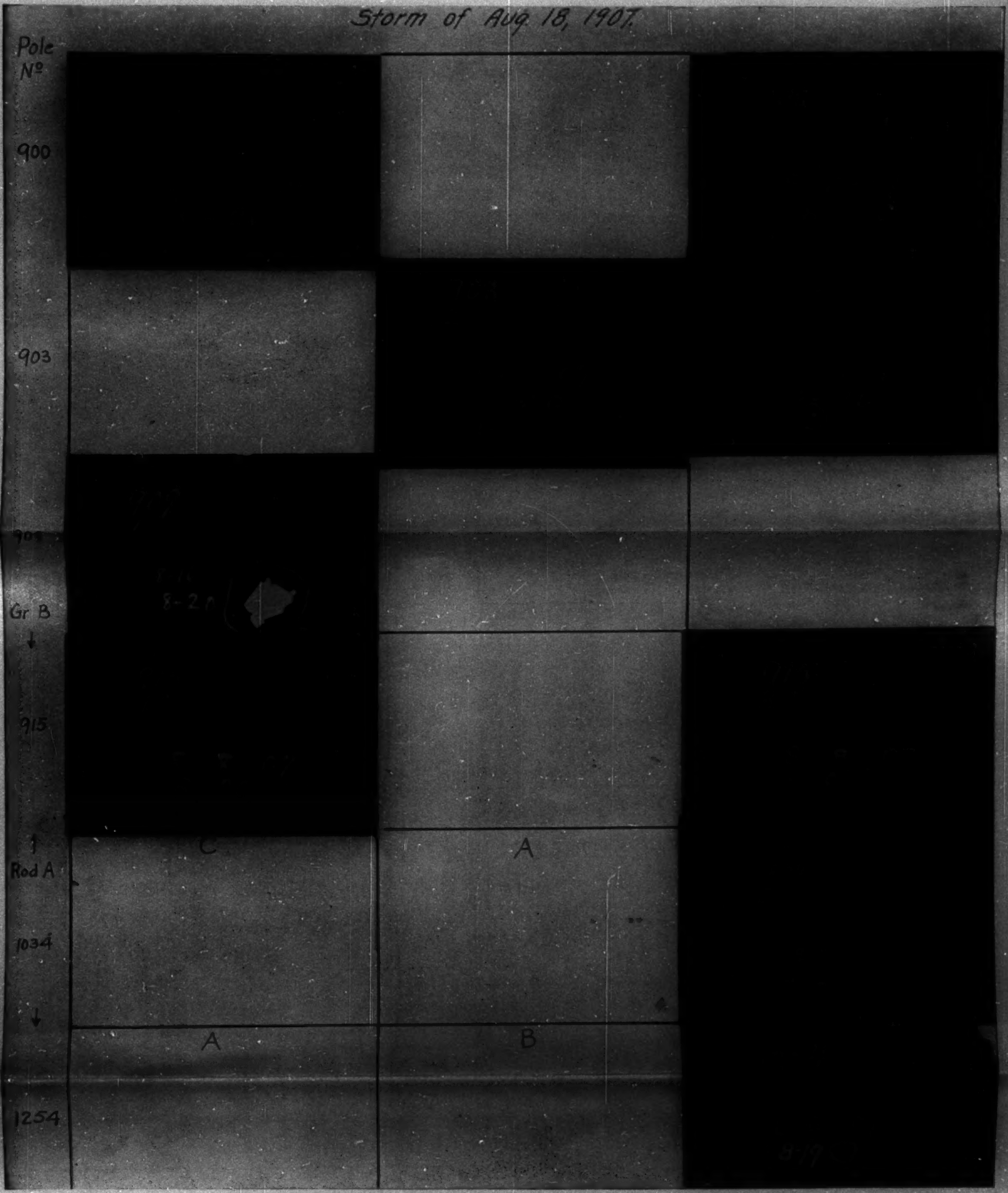
No.
B
A
301
8-9-07
8-19
108
406
1
2-16-07
8-19
2
A
A
B
834
3
8-15-07
8-20
837
3
8-9-07
8-20
834
837

Storm of Aug 18, 1907

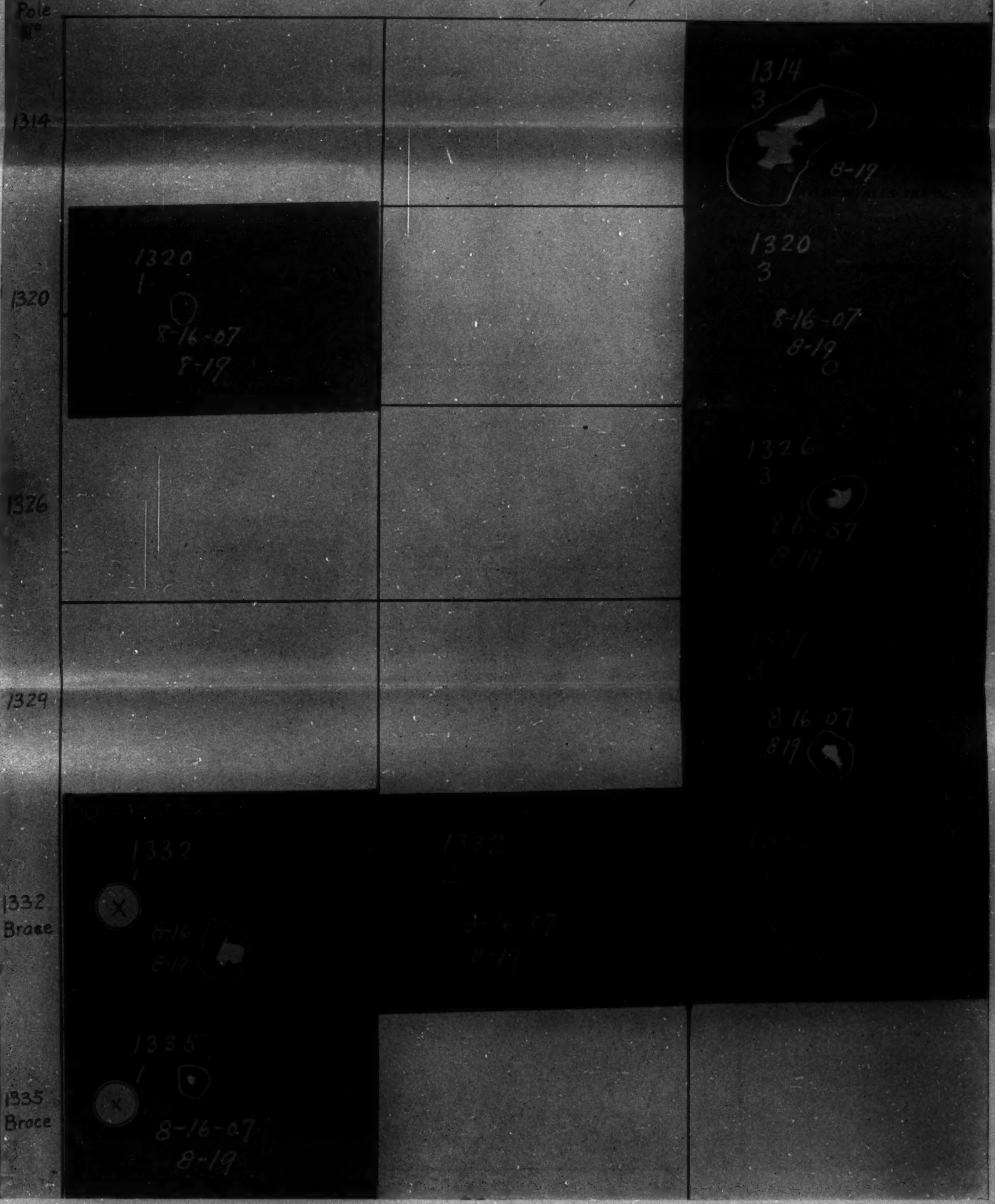
| Pole Nº | | | |
|---|---|---|---|
| 840 | | | 840 ⊙<br>3<br>8-15-07<br>8-20 |
| 879 | | | 879<br>3<br>8-8-07<br>8-20 |
| 885 | | | 885<br>3<br>8-8-07<br>8-20 |
| 888 | | | 888<br>3<br>8-8-07<br>8-20 |
| ↑<br>Dr. B | | 891 | |

| | | | |
|---|---|---|---|
| 879 | | | 879<br>3<br>8-8-07<br>8-20 |
| 885 | | | 885 <br>3<br>8-8-07<br>8-20 |
| 888 | | | 888<br>3 <br>8-8-07<br>8-20 |
| ↑<br>Gr. B<br>891 | | 891<br>2 <br>8-8-07<br>8-20 | |
| 897 | | 897<br>2 <br>8-8-07<br>8-20 | |

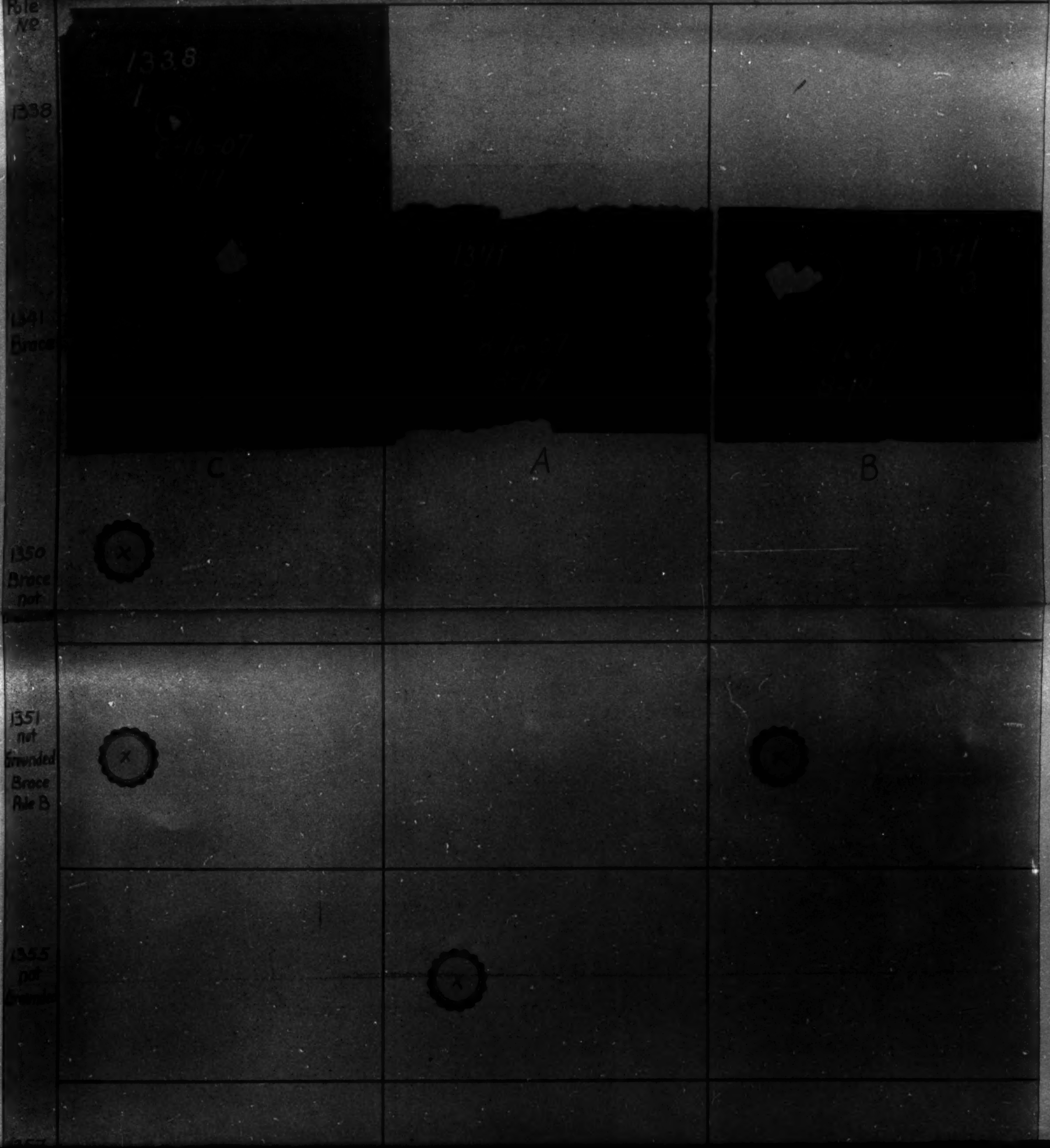
Storm of Aug. 18, 1907.

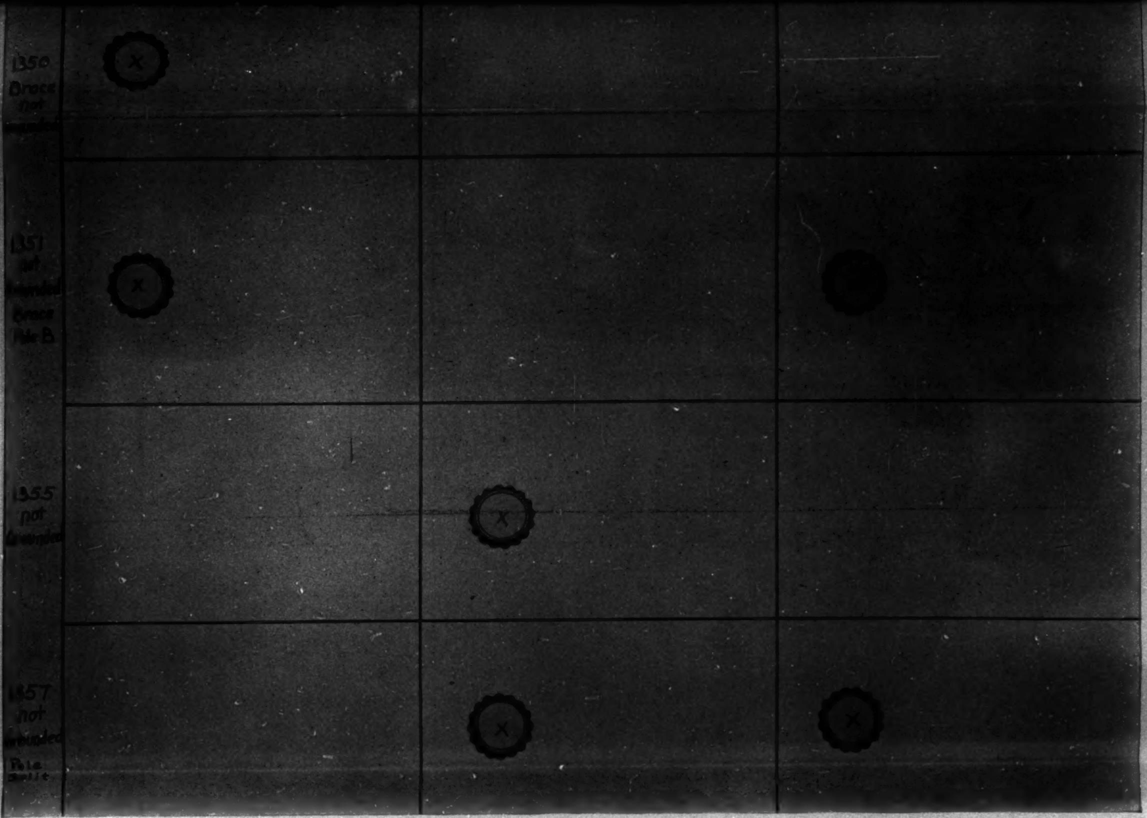

Pole Nº
900
903
Gr B ↓
915
↑ Rod A
1034
↓
1254
C
A
A
B

Storm of Aug. 18, 1907

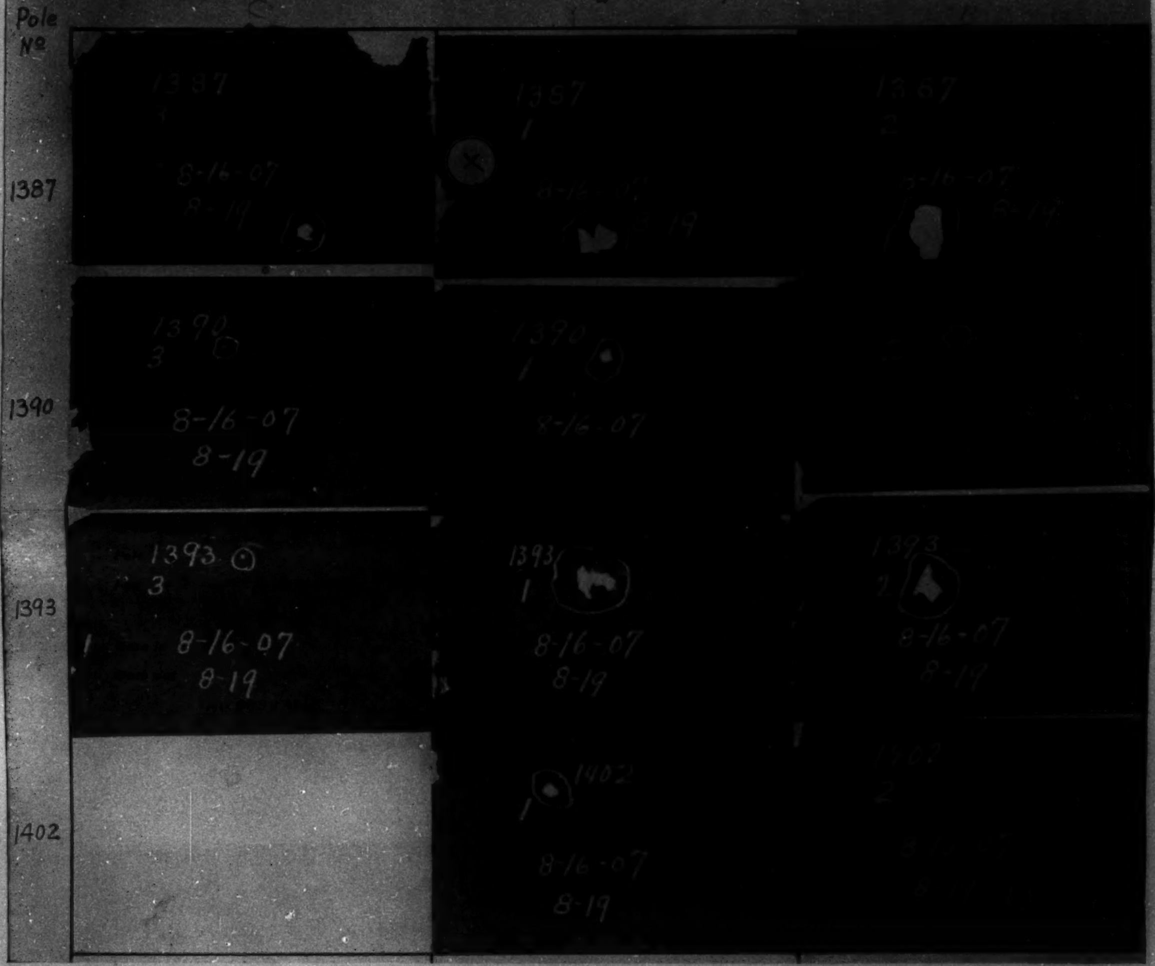

Pole N°
1314
1320
1326
1329
1332 Brace
1335 Brace
1314
3
8-19
1320
3
8-16-07
8-19
1320
1
8-16-07
8-19
1326
3
8-16-07
8-19
1329
3
8-16-07
8-19
1332
1
8-16
8-19
1332
2
8-16-07
8-19
1335
1
8-16-07
8-19

Storm of Aug. 18, 1907.


Pole No
1338
1341 Brace
1350 Brace not
1351 not Grounded Brace Pole B
1355 not Grounded
C
A
B
1338
1341
1341

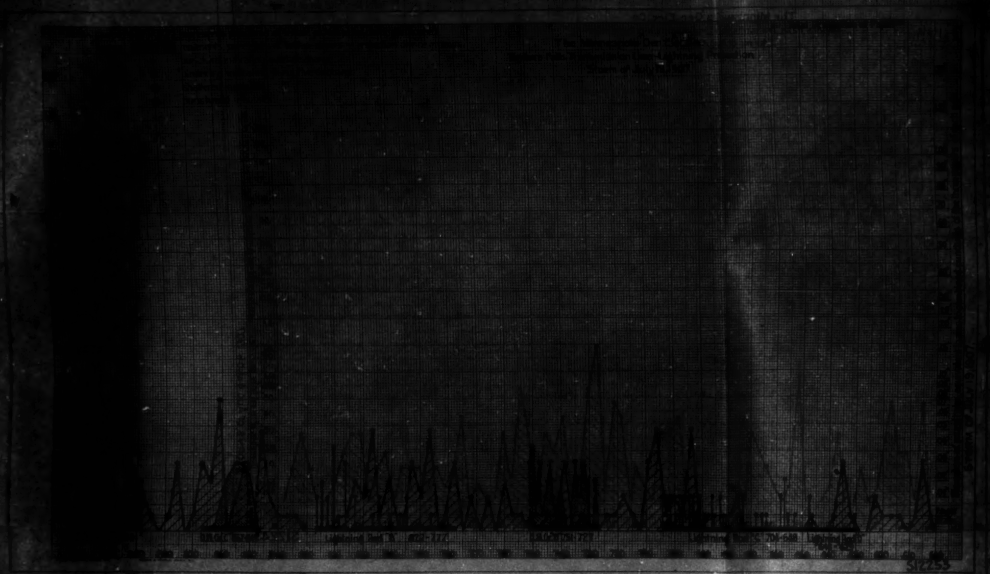

1350 Brace not grounded
1351 not grounded Brace Pole B
1355 not grounded
1357 not grounded Pole Split

Storm of Aug 18, 1907


Pole No
1387
1390
1393
1402
1387 3 8-16-07 8-19
1387 1 8-16-07 8-19
1387 2 8-16-07 8-19
1390 3 8-16-07 8-19
1390 1 8-16-07
1393 3 8-16-07 8-19
1393 1 8-16-07 8-19
1393 2 8-16-07 8-19
1402 1 8-16-07 8-19
1402 2

Storm of Aug. 16 1907

| | | | |
|---|---|---|---|
| Pole №<br>1405 | | | 1405<br>8-16-07<br>⊙ 8-19 |
| 1408 | 1408<br>3<br>8-16-07 | | |
| 1417 | | | |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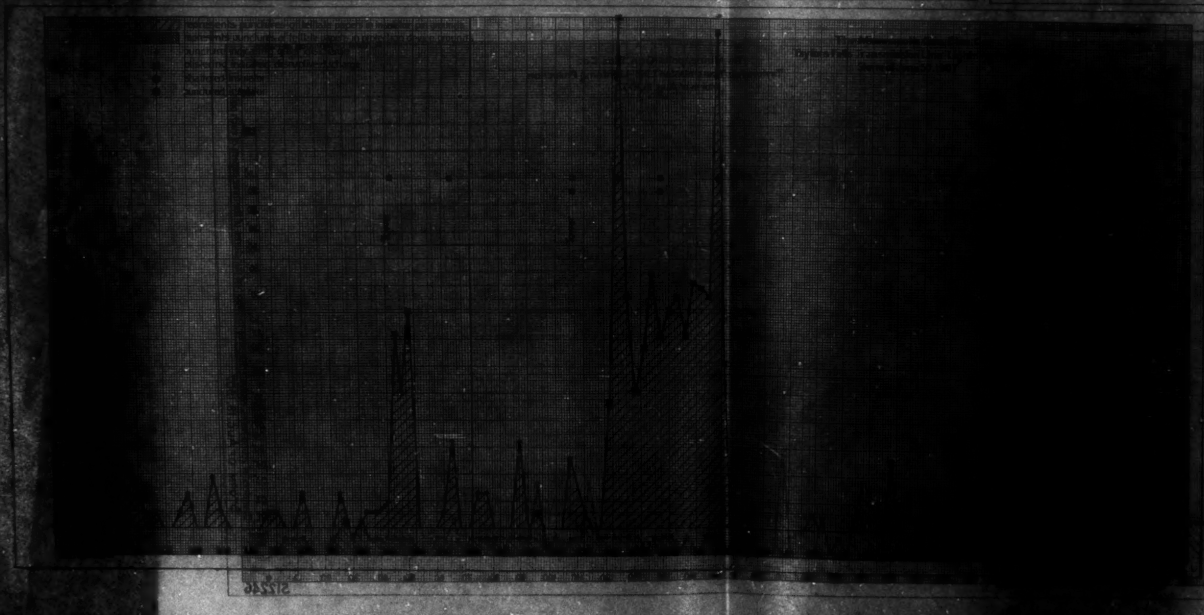
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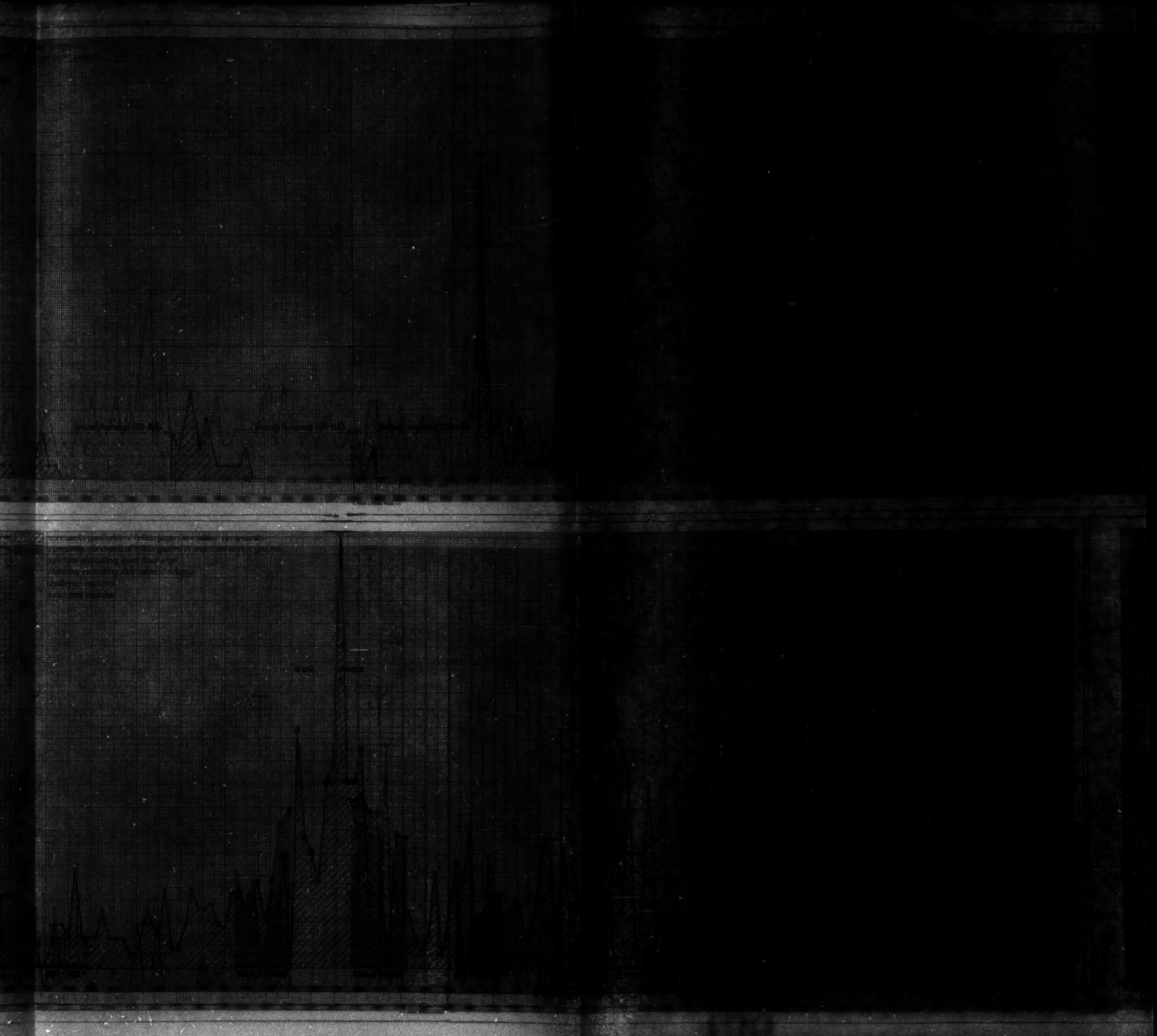

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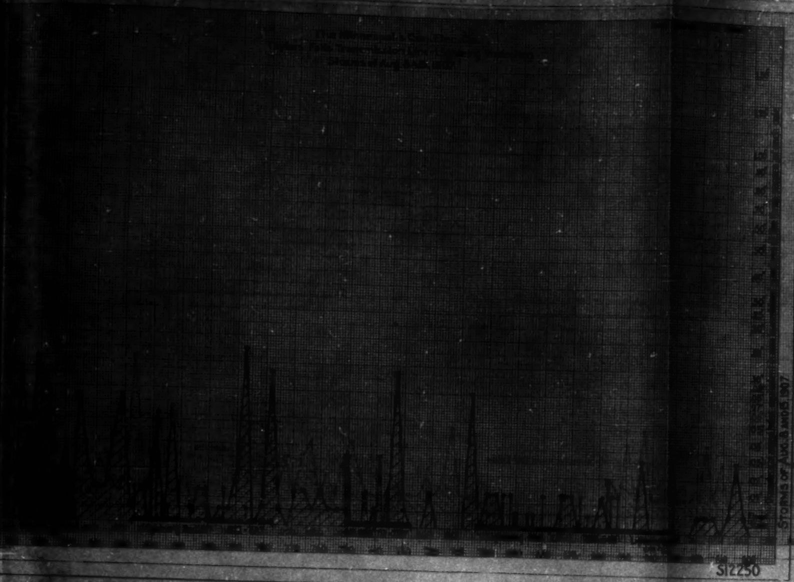
STORMS OF AUG. 8 AND 15, 1907
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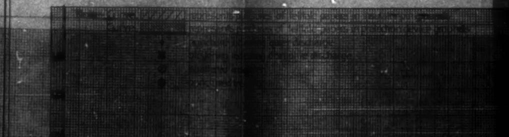

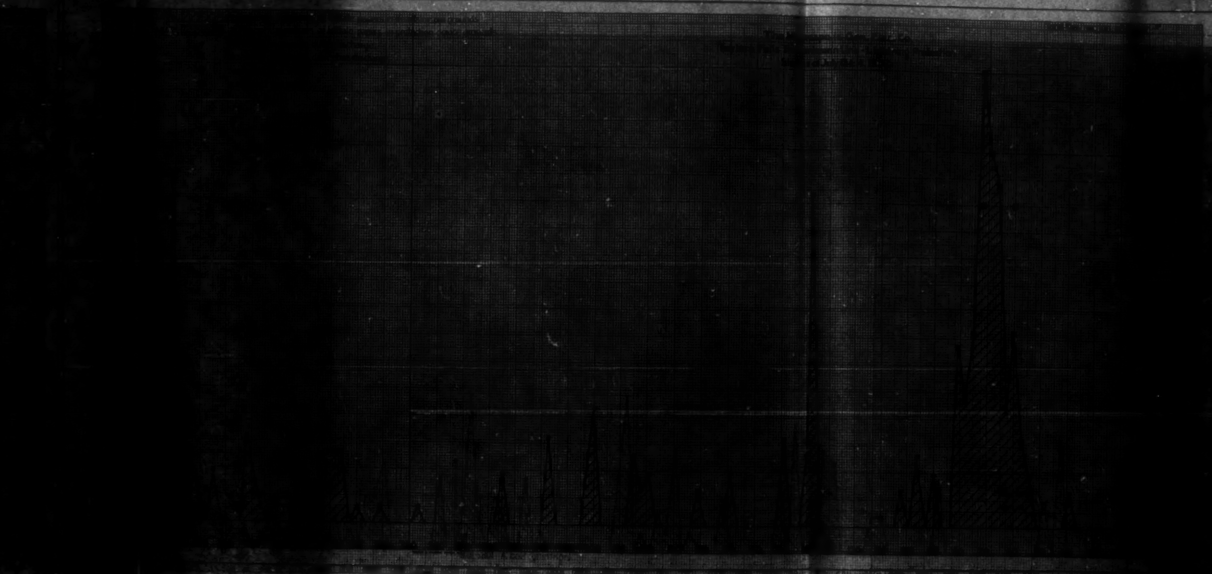

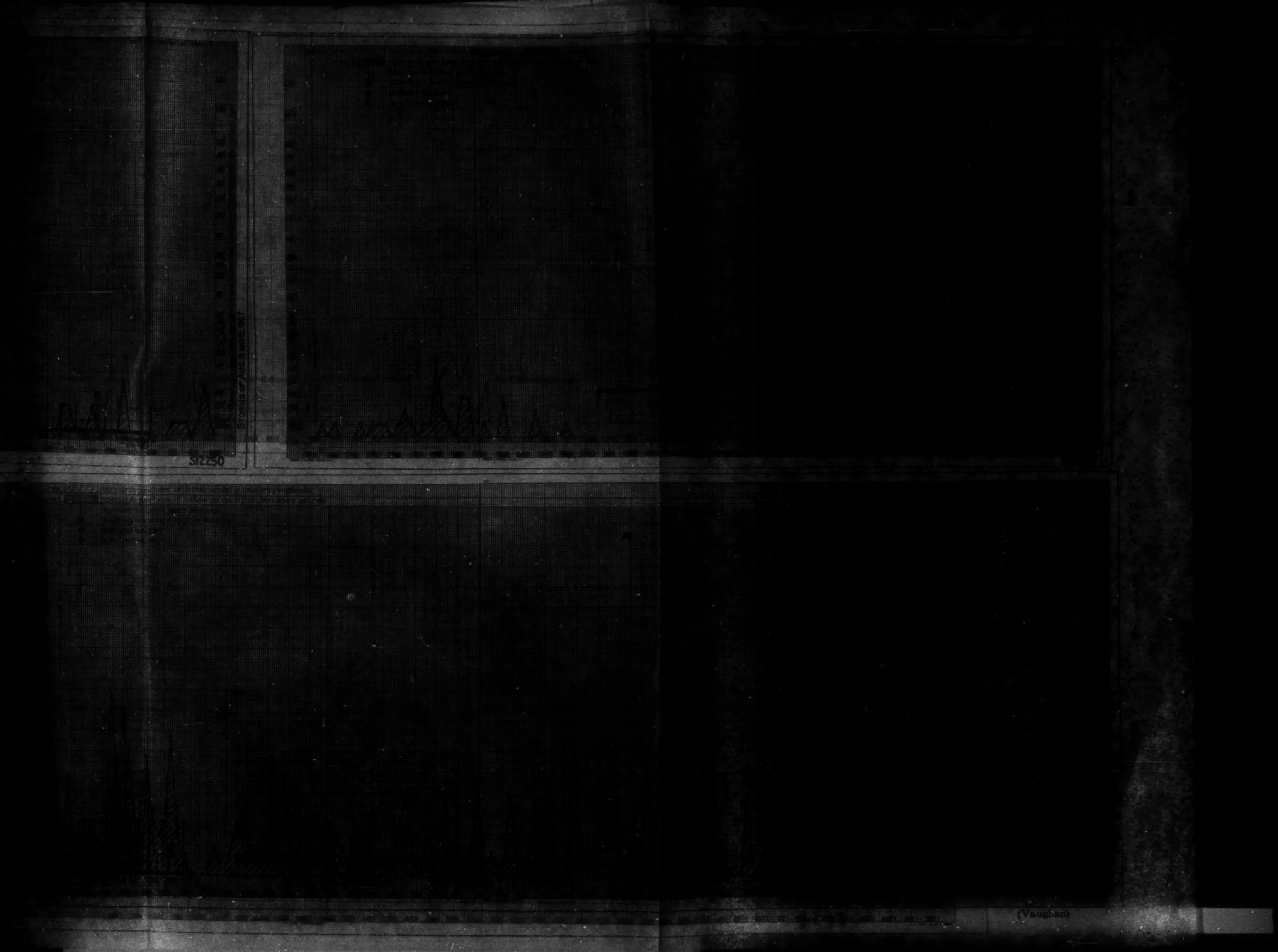

(Vaughan)

line from induced static charges and in preventing insulator breakdowns.

In the only case of direct stroke, the lightning-rod pole alongside the line was effective in preventing line damage.

A grounded conductor running down the pole is of decided value in preventing splintering of the pole.

The selective resistance, multigap type of arrester is effective in disposing of ordinary disturbances.

The aluminum cell-type arrester is, in general, more sensitive and freer in discharge; it gives great promise for station protection.

Horn arresters of the series gap and selective resistance type are fairly sensitive to static discharge as well as to disturbances of lower periodicity, and of special value as emergency devices to relieve the station arresters in case of abnormal discharge. They may be adjusted to be fairly sensitive without interrupting service or necessarily throwing out synchronous apparatus.

The use of the tell-tale-paper system is essential in following the action of station protective apparatus, and is of decided value in studying line stresses and the effectiveness of protective devices.

The results of the above experiments have led to the recommendation that the overhead grounded wire construction (Fig. 13) be immediately extended about 15 miles in sections covering both ends and the more exposed parts of the line; that the use of horn arresters be continued and further adjustments studied; that the rest of the station and line protective apparatus be left as it is; and that the present system of tell-tale paper and other records be continued during the coming season.

*A paper presented at the annual meeting of the American Institute of Electrical Engineers, New York, May 19, 1908.*

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# STUDIES IN LIGHTNING PERFORMANCE, SEASON 1907

BY N. J. NEALL

It is intended to discuss in this paper the general import to high-tension transmission of the data gained in 1907 as to lightning performance on the Taylor's Falls line, 50,000 volts, of the Minneapolis General Electric Co., and on the Presumpscot Electric Company feeders supplying power at 11,000 volts to the Cumberland Mills, near Portland, Me.

By reference to the description of the Taylor's Falls situation given by J. F. Vaughan, it will be obvious that in this case *line* disturbances chiefly are being combated; whereas, in the case of the Cumberland Mills, *station* disturbances have demanded attention.

These two classes of lightning disturbance will be considered separately in this paper.

## LINE DISTURBANCES

Lightning disturbances to a long-distance transmission line may be due to an induced (bound charge on the line) direct stroke, or both.

*Bound charge.* This idea embodies the well known principles of the operation of a static charge imparted to any insulated body. When this charge is gathered from an electrophorous in demonstrating elementary principles of electricity, the amount of charge, its potential, rate of accumulation, and rate of leakage, are, certainly of small values compared with those, at least, that we consider in electrical engineering to-day, not to speak of what we imagine the magnitudes to be in lightning phenomena.

A modern high-voltage transmission line must be highly insulated from ground at every point: for 60,000-volt service, therefore, it is easily conceivable that, in general, a tremendous electric charge can accumulate on the lines—assuming of course perfect equipment—and be held there with relatively small leakage. When in such a case as bound charge release takes place from the line, due to the discharge to ground, or to another cloud from the exciting cloud, an enormous rush of discharge undoubtedly follows the first point of breakdown to earth. Now since this discharge may be well extended beyond the point of maximum strain, there is relatively a considerable *flow*, once the discharge begins. This flow can be conceived as taking place over a wide area, changing from a sudden or explosive character at the centre of the strain area to a gently quiet one at the more remote points.

Theoretically, there are no ready means of determining how great such an area might be; it depends on a variety of conditions, such as extent of clouds, the degree of their electrification, their direction and rate of travel, etc. Practically on the Taylor's Falls Line it has been shown that they may be as great as several miles in extent of line, or as short as 1000 feet, approximately. From the operator's standpoint, the worst these clouds can do, or at least the usual average, is the desired information.

It has been shown that all such charges, once they are free to move tend to travel in waves, the progress and amplitude depending on the resistance in their path. In a limited length of line it may be easily possible to have the wave travel the whole length of the conductors, and be reflected at the open ends. This has shown itself prominently and repeatedly in the overhead grounded wires section tested by the Stone & Webster Eng. Corp. (See paper by J. F. Vaughan).

The tendency of such charges to travel in the transmission line is undoubtedly retarded very much by the skin-effect of the conductors; in fact, at the moment of release of bound charge we may consider that the charge has the choice of dissipating itself in three ways—along the line wires, over the insulators, or both. If the insulation is particularly good the charge endeavors to travel along the conductors. Its natural rate of doing so would be very high, in consequence of which there is a constant compromise between impeded progress along the wires and tendency to discharge over the adjacent insulator to ground. When the latter occurs, the rate of discharge is also likely to be again *suddenly* changed, and this, together with the absence of any inductance in the discharge path, is probably why tell-tale papers in such paths of discharge show violently explosive punctures.

*Effect of discharge.* From the data presented by Mr. J. F. Vaughan it has been shown that such discharges can be very violent and yet not harm the insulator, or produce a short-circuit. It has also been indicated that the discharges can be apparently of considerable length (compare static machine sparks) and yet make but a very fine hole in a tell-tale paper inserted in the discharge circuit. The presence of a thin long arc, or spark, which would of course be most pronounced in the case of " slow discharge over a high voltage insulator, is then to be thought of as the detrimental factor in the failure of insulators from this cause.

Now, curiously enough, there is very little trouble reported from lines operating at lower potentials, even at potentials of 30,000 volts. If the theory advanced herein before as to the formation of static strains on a line holds true, then every electrical line must undoubtedly receive such strains. It is, then, an important question—why well extended low-voltage lines do not lose insulators more frequently? The answer is probably partly this: No line can take a charge much in excess of its maximum insulator arcing-over strength. The result is, therefore, that the higher voltage lines must handle a proportionately larger and higher potential static disturbance. The character of the insulators for this purpose, especially when one considers them as special forms of high-tension condensers, undoubtedly has a still further bearing on the damage resulting to the line. The tendency in high voltage insulator designs to form long " anticipatory " sparks and arcs is well known among insulator designers; this helps, therefore, to form a conducting path for the line voltage to produce grounds, short-circuits, or punctures, as the case may be.

Again the action of the insulator under simultaneous static discharges and line voltage may have an important bearing on such failure.

From the data gathered thus far from Taylors Falls Line I would conclude:

1. That a bound charge can be impressed on a transmission line, with an extent from approximately 1000 ft., perhaps less, to several miles.

2. That its presence at any particular spot cannot be predicted, and, save for well known locations established after years of

careful observations, must be expected at any part of the line.

3. That it may occur successively at a number of points on the line, provided the exciting storm-centre travels along the line, and that the line is long enough to meet the necessary lulls between disturbances, or recharging of the clouds.

4. That there is no measure as yet of its maximum magnitude, but there is reason to believe that this is very great.

5. That the better the insulation the greater the concentration, and consequent disturbance once the charge can start to ground.

6. That the size and shape of the insulator determine the character of the spark which passes to ground, and govern failure.

*Direct stroke.* The phenomena of spark-gap performance in measuring high voltages, or in discharging a static machine, may be profitably utilized in order to understand the action of direct strokes of lightning as they affect an electrical transmission line.

In order that a line may be struck at all it must lie directly in the region of greatest strain; that is, form one of the electrodes of the lightning spark-gap, the other being the distant cloud. As the strain gradually increases between the earth and the cloud, the poles of the transmission line simultaneously respond to the new conditions. Even though they are thought of as being partial insulators, this makes no difference in the preliminary stages of this phenomenon. At the same time the transmission wires are accumulating rapidly a heavy bound charge. As soon as the flash occurs, it may at first strike a pole directly, and only later take the path via the transmission wire over the insulator, once the escape to ground of the bound charge has thus paved the way.

Again, the flash may actually occur between the transmission wire and cloud, because in the gradual preliminary increase of potential strain the effect of the insulator, so far as the static equilibrium is concerned, is comparatively nullified. In either case the result is the same—shattered poles, if of wood, and perhaps shattered insulators.

Upon reflection, it is clear that the common expression, " to be struck by lightning ", is technically incorrect; for any terrestrial object that becomes an electrode for a lightning stroke, plays as strong a part as the complementary part of the exciting cloud. It is the behavior of the electrode when the spark passes that determines its resultant condition. To this may be ascribed the peeling off of the bark of a tree, shattered chimneys, etc., and may be conceived as effects of repulsion inherent in the articles themselves, either from electrical causes or excessive local overheating.

In the ordinary conception of direct strokes only one stroke is thought to pass between cloud and ground, but it is also known that direct strokes often consist of light branch strokes as well as the main stroke. Since, moreover, the line under strain presents a variety of points along which such discharges may play, it is easily conceivable that failure of the insulators may occur almost simultaneously in several adjacent parts of the line.

Photographic study of lightning flashes shows that it is apparently oscillatory, and there are in fact many strokes in an indefinitely short time, although the eye may see only one.

From the data at hand (Taylor's Falls) it appears that the *current* flowing at such times may be relatively small as compared with the lightning voltage. We then have on a grand scale a duplication of the static-machine sparks, and others of a similar nature.

The remaining primary disturbance is the discharge between cloud and cloud. If these are far enough away from the line the effect can be neglected, but owing to their generally low altitude such a discharge can either cause a release in the line of bound charges of opposite sign parallel thereto, or a secondary discharge between the clouds and line or ground as the case may be.

In either event the effect on the line is essentially the same as described in the preceding discussion, and may be either simple or complex; that is, at present, unless actually observed, it is impossible in some cases to tell exactly whether a transmission line disturbed by lightning has been affected by induced or direct stroke.

## GENERAL

*Effects of the nature of wireless waves.* In addition to the conditions described in the foregoing paragraphs, there are undoubtedly minor disturbances created in the line by the action of the lightning discharge as a source of high-frequency waves which, reaching the line, are absorbed in a manner similar to that of a receiver in wireless telegraphy. This absorption may be more rapid than the line can dissipate, and the result is either a surge of " static ", or, even worse, a discharge to ground, by reason of the impedance of the line wires to the free travel of the waves.

The result is, therefore, the same as in the preceding case—the imposition of a high peak of static on the line which tries to seek a level of zero value by traveling off in either direction on the line.

*Effects arising from inherent characteristics of line construction depending on:*

*a.* Insulator characteristics. An insulator for high-tension service is a form of condenser made up of a number of condensers (petticoats) of larger capacity, placed in series between line and ground. The best interest of the designer is, therefore, so to apportion his parts as to insure a uniform distribution of strain best suited to the service required. When this is but poorly attained there occurs the well known failure of insulators on test by premature puncture of one of the parts.

In addition to the absolutely essential qualities of ruggedness, high-class dielectric strength, and good finish, an insulator for such service must have a strength against arcing over at normal frequency at certain values previously determined upon by the designer. In general, insulators are designed not to arc over at below twice the voltage of the system on which they are to be used when subjected simultaneously to some such rain test as 0.25 in. per min. driven against the insulator at an angle of 45°. This, so far as it imitates nature, is of course very severe, and gives for any design a much lower voltage of arcing over than would be obtained with the insulator dry.

In testing such insulators the usual practice is to raise the voltage fairly quickly until arcing over occurs; if this falls below the desired voltage the design must be changed. An insulator can, in general, stand a higher voltage thus administered than voltage applied continuously.

Some insulators are designed for large total lengths of surface to prevent leakage; and where this is not likely to be linked with severe lightning disturbances the design of the insulators can be made in a different way. It might be said, however, that the insulator thus designed is likely to make a poor showing under rain test, while it is not at all improbable that for all-round service the insulator well designed for lightning and rain may do well in the leakage class. It is not the purpose of this paper to consider the latter.

On the rain test at present, therefore, we look for characteristic performance. Two phenomena exhibit themselves: first, the static strain, or envelope of the insulator repulses the drops of falling rain away from itself; secondly, the combined forces of static repulsion and mechanical deflection of the falling rain give rise to a resultant direction of rain, which, if the inner petticoats are not properly shaped, throws the water directly under the top petticoat. In general this has been found to be most pronounced in curved petticoats and absent in straight parts when properly inclined. It is obvious that the former condition is very harmful to the strength of the insulator under high-potential strains. In addition to this, many insulators give evidence of internal unbalance long before breakdown. This usually means an insulator very liable to puncture.

So far as the insulator used on Taylor's Falls line is concerned, I wish to state that standard tests which I have made independently on this type show a satisfactory performance along the lines indicated in the preceding; this leads me to think that its characteristics are of distinct value in the lightning problem now under consideration.

Now the preceding characteristics apply entirely to insulator performance at *normal* or commercial frequencies. At higher frequencies there is as yet very little data, but the following ideas may be tentatively considered as an aid to the present discussion.

*Equivalent spark gap.* In testing insulators to date no consideration has been given to their equivalent spark gap. For very high voltage insulators this is hard to secure for the general want of adequate apparatus but, it is undoubtedly within the reach of some. The principle involved is this: that while an insulator may have a very good performance under normal frequencies, it may be very poor at high frequencies, or their equivalent.

*Nature of discharge.* It is not inconceivable that the discharge over an insulator may be tenuous as well as abrupt. If tenuous, the shape of the petticoats once again materially affects the disposition of the arc, and possibly causes a fracturing by means of the intense local heating and the consequent unequal expansion of the porcelain. There may also be " percussion " effects due to the sudden change of atmospheric pressure around the insulator at the time of arcing over, and thus fracture an insulator. These ideas are based on the characteristics of shattered insulators on the Taylors Falls Line.

*Simultaneous static discharge with line voltage.* This is the equivalent of static discharge over a lightning-arrester with voltage simultaneously present. In the case of insulator performance, the object of the investigation should be to determine the degree of non-arcing power of any given design under the conditions noted.

b. *Mechanical design.* The nature of the line construction, whether of wood, or entirely of metal, the length of span, size of insulator, number and nature of braces, etc., determines to a large extent the degree of damage any lightning disturbance will cause. If the poles are of wood, splintering of the poles may often occur, sufficiently, at that to require renewal of the support. Short spans naturally subject more poles to disturbance, within a given area, and, therefore, to more likelihood of damage. Large spans on metal towers invite more trouble (relatively at a given support) because of their isolation and attraction for the charge.

c. *Line profile and local topography.* Attention has long since been called to the relation between the topographical location of the line, and it vulnerability to lightning. In any layout of importance the profile, or cross-section of contour, should be made in order to show the maximum and minimum elevations and relations of hills to valleys in the line. Where geological formations are known, the extra information thus given is of value in determining the probable points of discharge between cloud and ground, provided the general direction of a storm is also fairly well established. This feature has been demonstrated on the Taylor's Falls line by the apparently greater vulnerability of the west side of the line over the east, direction of storm from northwest to southeast. It is also thought that lightning has shown a preference for striking high elevations of the line and in damp, swampy places.

d. *Proximity of sub-stations.* It is just as possible for a lightning discharge to occur near a power station as not, in which event ordinary lightning protection would be heavily affected. It is doubtful whether any device now proposed for station protection, exclusive of horn lightning arrester without appreciable effective resistance in series, could handle successfully a release of heavy bound charge, etc. It is, therefore, important to insure adequate protection at such points. On the other hand, the tendency of line disturbances to concentrate might render any station immune if sufficiently remote therefrom. These conditions have been amply illustrated on the Taylor's Falls line.

## METHODS OF PROTECTION

From the data given by this line, and on the basis of the preceding considerations, both theoretical and practical, the following methods of obtaining protection against line disturbances from lightning may be considered:

1. *Overhead grounded wire.* Judging alone from the data now at hand as to its behavior, an overhead grounded wire placed near the line conductors may be considered beneficial. Apparently, it is not necessary for the grounded wire to be above the transmission wires in order to absorb a certain portion of the static charge. This has been positively measured in the case of the grounded wire in the centre of the triangle on the Taylor's Falls Line, and is doubtless helpful in reducing the strain. Its limitations in this respect are obvious, especially when it comes to increasing the amount of ground wire protection over that given by one wire.

The ideal static protection, as is known, would be a metallic envelope for the line; but since this is not commercially feasible, it is thought possible to approximate it by supporting several grounded wires above the line. These wires are so placed with reference to the line wires that an imaginary plane, extending at an angle of 45° from the wire on either side of centre, will just pass over the transmission wire. There are as yet no positive data to show the value of this consideration, but there are data of a definite nature showing the effectiveness of the double-wire overhead grounded-wire protection.

When the possibility of simultaneous direct stroke is borne in mind, a further disadvantage of the grounded wire placed *within* the triangle is at once apparent; for a direct discharge between this wire and cloud is not easily conceivable, certainly not so conceivable as in the external arrangements of grounded wires where the possibility of divergence of direct stroke is better prepared for.

The experimental data on this performance have not yet fully and completely established the superiority of type, but there is certainly good reason to think that an overhead grounded wire protection, consisting of several wires supported above the line, is good protection. This protection should reduce the disturbance to the line to a very small amount indeed. In fact, the power of absorption shown by such protection leads to the conviction that if a transmission line were so equipped throughout, very little static disturbance would ever reach the stations;

in other words, the overhead grounded wire would not only shield against the line troubles, but reduce consequent station disturbances.

2. *Lightning-rods*. There is evidence to show the value of lightning-rods to a transmission line, particularly in that case of Taylor's Falls where a lightning-rod was struck and the telltale gaps on the line adjacent thereto showed no disturbance. This diverting power is certainly of value. Two methods of application are feasible, first, as an additional feature of line protection placed separately but adjacent to the line at points known to be particularly subject to this effect. Since the latter is at best uncertain, I prefer the inclusion of a lightning-rod with the overhead grounded protection at frequent intervals throughout the line. On a steel tower construction (solely because of the usually long spans) these should be placed on each tower; on a wood-pole line, one of these could be placed at each grounded pole. These rods should perhaps extend 4 ft. to 6 ft. above the overhead grounded wire, and end in spreading tips.

3. *Grounds*. The importance of good grounds for the overhead grounded wire is patent. Too great care cannot be exercised in this direction. The data given show that even on the grounded wire the passage of the charge to earth is apparently impeded, even by the short distance it had to travel along the line. For this reason it is clear that grounding at every hole is beneficial to the discharge. For ordinary line work time may prove that grounding every several poles is adequate, but that near stations or important points of the line, grounding at every pole is essential. This would be particularly desirable in the case of partial protection of the line where a stretch of overhead grounded wire was used to protect a sub-station. In this case the data as to the possible extent of such charges make two miles, approximately, the minimum limit of length out from the station that would secure nullification of any nearby induced disturbances.

4. *Extent of application*. It is an open question of economy whether to equip a line completely, or partially, with overhead devices; but in consideration of the charges which they may be called upon to carry *at any point*, the whole line protected is theoretically and generally the safer policy.

5. *Insulators*. The Taylor's Falls data show that while the overhead grounded wire appears to remove the greater part of

the stress, yet it should not be assumed that the remaining charge is negligible.

For this reason the selection of insulators for such a service should insist on as high quality as ever before. The criterion of approval should be a non-arcing at no less than double normal potential under rain test of 0.25 in. per min. at 45°, with pin grounded, or an equally severe test. Under such a test the insulator should be relatively free of premature arcs and sparks. No rain should be deflected under superposed petticoats, and thus promote breakdown. When possible the equivalent spark gap of the insulator should be determined, and should always be high, certainly giving a large margin over any standard lightning protective apparatus connected to the line.

The reason of this is patent from the performance of insulators on high-tension lines. It is clear that when the line is running with the neutral grounded the severity of service on the insulator because of the resulting short-circuit arc is certain to be quite destructive. In this respect the ungrounded system is better because the discharge over the insulator does not necessarily mean a short-circuit, or, if two insulators on opposite phases should simultaneously discharge, the resulting short-circuit may be favorably effected by the intervening resistance conditions involved.

The performance on the Taylor's Falls line brings out an important element of high-tension transmission line design; namely, the probable extra vulnerability of the insulators on all-steel towers, cross-arms, and pins. Where a section of wooden cross-arm intervenes between the insulator and the nearest ground it is possible to conceive of an increased arcing distance, which in the case of small insulators might be of some benefit in holding back disturbances. I therefore conclude:—If the insulator can be properly selected as to size, equivalent spark gap, arcing over voltage, and general characteristics, the nature of the tower construction may be neglected, particularly if overhead ground protection is present.

6. *Line choke-coils.* At the suggestion of Dr. C. P. Steinmetz, line choke-coils were originally included in the program of experimental equipment for Taylor's Falls Line, in order to determine by means of tell-tale gaps how far any given disturbance travelled along the line. The experiments from which these data were to be obtained were not carried out, but the choke-coil papers show that the coils operate freely under the static disturbances

which are now known to be present on the line. In consideration of the small inductance of these coils (1 ft. diameter by 20 turns, approximately 60 ft. of wire) the tell-tale indications of static rushes are most impressive.

The chief difficulty in such an equipment is in the construction of the choke-coil itself. For the Taylor's Falls line the coils were finally constructed of brass tubing, which has apparently been found reasonably satisfactory. It is yet too early to say whether such a feature can be of great benefit. The danger of such an equipment is the possible piling up of potential at the nearest insulator, and the consequent failure of the same.

7. *Horn lightning-arrester*. The horn lightning-arrester (essentially a simple spark gap of special form between line and ground) is, so to say, a hybrid—part station, part line device. In this paper it is considered solely as protection—extraordinary against great disturbances of any source reaching a sub-station or power house.

a. *Gaps*. I think it must be clear from even this one season's records on the Taylor's Falls Line that when a horn arrester is at the centre of a violent static disturbance, for example, a disturbance that affects the insulators, it will act as do the insulators—arcing freely over a large distance. In this way, by proper relative adjustment of the various gaps, severe disturbances near important points can be carried off without damage to either the insulator or the station apparatus. Judging from the magnitude of the static discharge as evidenced on some of the line tell-tale papers, it is a grave question whether standard station lightning-arresters could take care of anything like a nearby direct stroke. There is less doubt that the horn arrester could do so. In the case of grounding of the line, the horn gap will also operate, but in my judgment such action should be made as difficult as possible, in consideration of the sensitiveness of the electrolytic arrester to this effect. This leaves the horn arresters to care for emergency disturbances like a direct lightning stroke and high-power surges only.

On the Taylor's Falls plant there has been a pronounced evidence of the effectiveness of a number of gaps between line and ground operating on the selective path principle. In general the operation of the gaps has recorded both lightning disturbances and disturbed static balance from grounding of the system. In the former case all of the gaps between line and ground would operate, the tell-tale paper sometimes indicating a light discharge not followed by dynamo current, and again quite a heavy line current. The methods adopted apparently establish this action very well, irrespective of the arrangement of the resistances, whether directly in shunt as in the power house group, or directly in series, as at Hugo. The curious preference for the circuit through the fuse to ground at the power-house horn instead of from the shunt lead to ground—the resistance being relatively equal in all directions—shows forcibly the ease with which such disturbances take a long *air* path in preference to the regular circuits prepared for them.

b. *Resistance.* In the matter of resistances there are as yet incomplete data on the behavior of water, but certainly the operation of the last season did not exhibit any bad traits in this material. At the power house the water for the whole arrangement is supplied by the tailrace, and is, therefore, constantly renewed. Its resistance, however, is low. My fear was that a discharge to ground would go by way of the first path to shunt resistance, and thus directly to earth. I find, however, that it has apparently not done so, and I conclude that this is due partly to the superior character of the horn arrester " ground " reached through the fuse (see paper by J. F. Vaughan). The tanks at Hugo and at the sub-station have given no trouble. The amount of resistance best suited to the purpose is yet to be worked out. It may be that the size of receptacle employed, as well as the method of arranging electrodes,* has perhaps had an important bearing on this matter. The use of bituminized fibre conduit enables high insulation at the point of entrance of the leads, and controls the degree of electrode exposed in the water for the passage of the discharge.

c. *Operation.* In general, it must be borne in mind that if the horn is to carry any current, the *more* current it carries the better, so far as self-extinguishing power is concerned. This, however, is bad for the system, tending to pull out the breakers. The employment of light fuses so limits the discharge that protection is lacking where disturbances repeat themselves. The selective path multigap type of horn (gaps arranged in series as at Taylor's Falls and Hugo see paper by J. F. Vaughan) permits a better adjustment theoretically, to the variables of such disturbances, and insures less need of attention.

It is recognized that water resistances must be put out of commission in winter, unless special provision be made for keeping them warm. Where such apparatus is near a substation, this is not difficult. In such a situation as the middle of a long-distance transmission line it is still feasible but scarcely necessary. Since its chief use may here be considered in connection with lightning disturbances, there remains only the possibility of high-power surges which could be easily provided for by a proper adjustment of the horn gaps in series with a fuse. Even in this case a fuse might be retained of considerable current capacity, and depend solely on the gap action to relieve the strain.

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*This method was suggested to the author by Mr. John L. Harper.

It seems desirable to have the horns operate coördinately with the arcing over characteristics of the insulator. Since the grounding of the line may cause a momentary potential rise at some distant point, owing to the rush of line charging current to its new position of equilibrium, the setting of the first gap in a selective-path type should be approximately 150% normal voltage with reasonably high resistances. Too high resistance would impede the discharge. The total gaps in series should breakdown just under the arcing-over voltage of the insulators under its worst performance, usually taken to-day as at rain 0.25 in. per min., angle 45° with pin grounded. It were better with a single gap to have no resistance in series, only a fuse, to be set for the highest voltage.

These considerations are subject to change with increase in knowledge as to actual equivalent spark gaps of insulators, lightning-arresters, and horn air-gaps. It may be possible later to call for larger air-gaps, in the horns, because of its equivalent spark gap characteristics. The present ideas are recorded merely to illustrate the purposes and tendencies for the future in the Taylor's Falls installation.

A horn arrester should preferably not be called upon to operate on any condition which a standard station lightning-arrester could handle.

The bad effect of wind on the arc has been well indicated by both experiment and actual operation. This feature of horn lightning-arrester operation will always be a serious menace to a system at the time of simultaneous operation of two adajcent horns; it is a matter of chance which must be allowed, or elaborate preventive precautions must be taken.

8. *Special line-protection station.* The operation of the horn arrester group at Hugo (centre of the line) Taylor's Falls is critical in that it focuses the whole question of placing station type arresters on the line to draw off the static disturbances.

It is clear from the data now at hand as to the minimum area of local concentration of lightning line disturbances, approximately 1000 ft., that in order to do this fully a very large number of arresters (approximately six groups per mile) would have to be installed, and then, aside from the consideration of maintenance, there is the great question as to their reliability and sufficiency under the conditions. During the past season I have had a group of low-equivalent alternating-current lightning arresters, equipped besides with phase to phase protection, at the middle of a 11-mile, 11,000-volt line, in Maine, to assist in carrying off discharges from the line; for there has been considerable action at this plant from lightning. The characteristic of the performance of this system as a whole is a phase-to-phase operation, rather than from line to ground. Even though lightning storms were particularly frequent in this locality, and station protective apparatus at both the generating and step-down ends of the line operated freely, with considerable dynamic current manifested, the discharge at the centre of the line was nearly always lighter and colorless. To such a degree does this check the performance of the central arrester group on Taylor's Falls line, that I am inclined to conclude that for the majority of line disturbances, whether static or otherwise, a central group does little good. What a high-power surge would do is still an open question.

While these conclusions do not destroy, theoretically, former practice in regard to frequent placing of station arresters on the line, they seriously modify its practical value. By the theory advanced that the better the insulation of the line the more local the serious static disturbances will be, then line arrester stations decrease in value as the design voltage of the line increases. They thus become self-eliminating from our consideration.

9. *Miscellaneous.* So far as attempts have been made to protect against line disturbances by larger insulators, or special features at insulators, such as horns to modify the effect, it is clear there is no reduced interruption to service itself when discharges actually occur. For this reason I should prefer, where feasible, any protection scheme which aims to prevent the static disturbances getting on the line at all.

## STATION DISTURBANCES.

The characteristics of this feature of lightning disturbance to electrical apparatus are too well known, and too fully discussed, to need further mention here. For the sake, however, of new corroborative data, which I now wish to offer, I will summarize the phenomena as follows:

1. Lightning effects causing line-to-ground disturbances.
2. Line-to-line disturbances.
3. High frequency (or equivalent) and low frequency.
4. Internal disturbances due to grounding of line, short-circuits, etc.

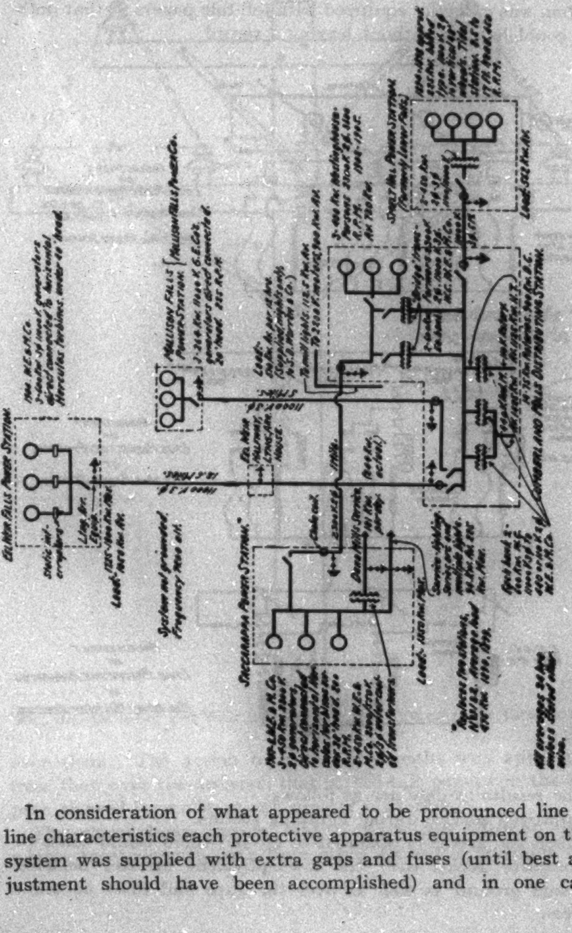
*Line-to-ground.* From the station data at Taylor's Falls power house, as well as from the Minneapolis sub-station, the frequent and full operation of all types of station protection is fully established. As has been stated by Vaughan, throughout the season of 1907 no apparatus was hurt by lightning, save in the case of one transformer bushing, which failed by grounding.

The lively operation of the apparatus, as evidenced by the action of the series and shunted gaps, respectively, and the heavy discharges over the electrolytics, indicate a considerable strain to ground, which for the present must be considered effectively handled by the protective apparatus.

The size of the punctures over the low-equivalent alternating-current arrester does not differ materially from similar data on apparatus for lower voltages. In consideration, however, of the data now at hand as to the action of static discharges on the line and the effect on tell-tale papers where free discharge occurs, there is a question whether or not station lightning protective apparatus must not be limited in action to reflected or transmitted disturbances of lesser magnitude, and to such disturbances as are generated in the system itself. Certainly, commercially we cannot expect more than this. Comparing the action of the various types, it has been shown that no arrester shunts the other entirely. Thus while from the response to ground the greater sensitiveness of the electrolytic is apparent, yet in case of greater severity all arresters operate.

I recognize that, theoretically, both types should operate at the same point, but in the case of the electrolytic arrester the possibility of a closer adjustment to circuit conditions without consequent short-circuit is greater than in the low equivalents or other multigap resistance types of arresters.

At the plant of the Presumpscot Electric Company, previously referred to, a large amount of experimenting has been carried on for the last two seasons, and is still under way. This plant consists of three hydroelectric stations feeding a central distribution station, (Fig. 1) where the power at lowered voltage is conveyed to a large synchronous converter load and induction-motor load respectively, one of the stations generating directly at 11,000 volts.


EEL WEIR FALLS POWER STATION
MALLISON FALLS POWER STATION
SACCARAPPA POWER STATION
STEEP FALLS POWER STATION
CUMBERLAND MILLS DISTRIBUTING STATION
11000 V. 3 ϕ
11000 V. 3 ϕ
17 Mile

DIAGRAMATIC SKETCH OF TRANSMISSION LINES. PRESUMPSCOT ELECTRIC CO.

FIG. 1

In consideration of what appeared to be pronounced line to line characteristics each protective apparatus equipment on this system was supplied with extra gaps and fuses (until best adjustment should have been accomplished) and in one case low equivalent arresters were placed across the line. In addition to this the regular low-equivalent arresters between line and ground were shunted with gaps and fuses, two each, around the shunt and series resistances in series, (Fig. 2). The whole system was carefully equipped with tell-tale papers so that nothing could happen without leaving a record.

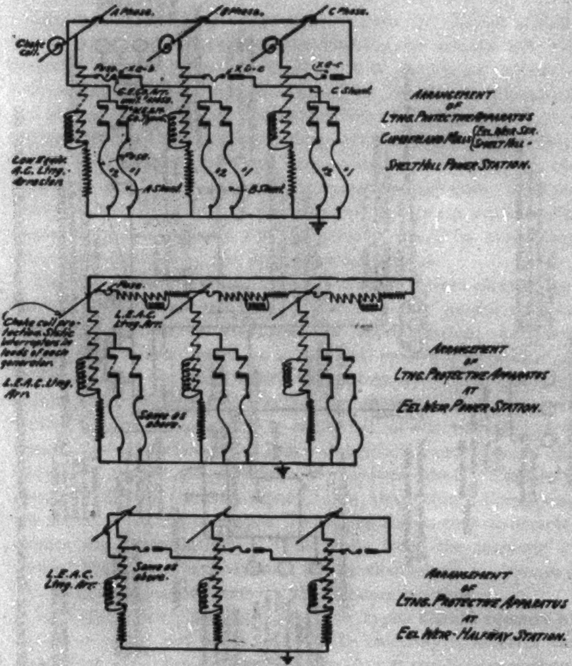

A Phase.
B Phase.
C Phase.
Choke Coil.
Fuse.
C Shunt
A Shunt
B Shunt
#2
#1
Low Equiv. A.C. Ltng. Arresters
Arrangement of Ltng. Protective Apparatus Cumberland Mills {Eel Weir Sta. Skelt Hill - Skelt Hill Power Station.
Fuse.
L.E.A.C. Ltng. Arr.
Choke coil protection. Static interrupters in leads of each generator.
L.E.A.C. Ltng. Arr.
Same as above.
Arrangement of Ltng. Protective Apparatus at Eel Weir Power Station.
L.E.A.C. Ltng. Arr.
Same as above.
Arrangement of Ltng. Protective Apparatus at Eel Weir-Halfway Station.

FIG. 2

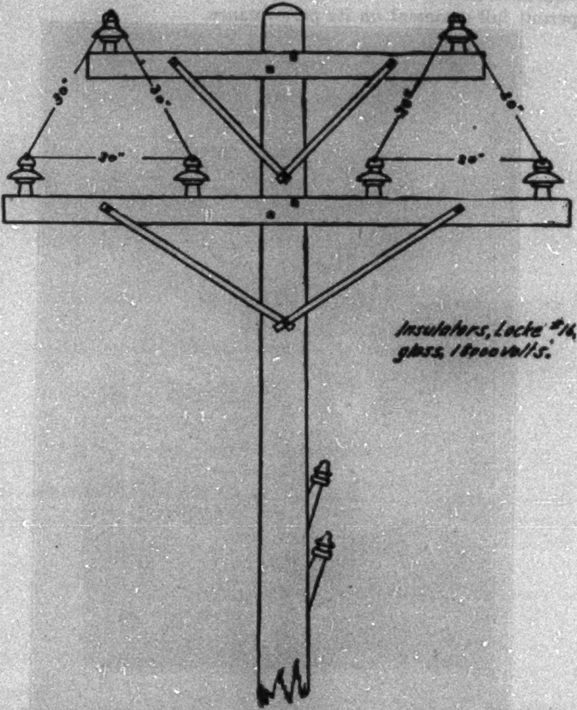
The results to date are as follows:

Improved service during lightning storms.

When the arresters operated to ground there would often be a complete action over the low-equivalent arrester between line and ground as well as over the gaps and fuses in shunt thereto.

In any given discharge not all the fuse paths to ground would operate. Fuse paths in operation would sometimes blister the paper badly, again a paper would show burning.

Fuses did not always blow even though a discharge had passed over them. The action over the fuse paths was apparently freer than over the arrester; that is, tell-tale papers on the fuse path showed larger holes and greater blistering.



Insulators, Locke #16, glass, 18000 volts.

Fig. 3.—Detail of Eel Weir line construction Presumpscot Electric Co.

The shunted-gap papers seldom show any current, from which, together with data from other sources, I conclude that the dynamic *current* seldom passes over the shunted gaps. It is the static or disturbing voltage only.

A new type of selective resistance arrester was installed last season, but too late to give much information. It has operated on several occasions, but there are as yet insufficient data to permit full comment on its performance.

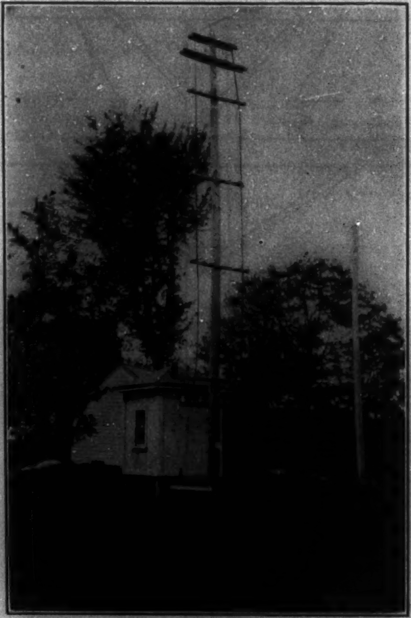


Fig. 4.—Presumpscot Electric Co. View of Eel Weir half-way line lightning arrester house

*Line-to-line.* The results in this item at the Presumpscot Electric Company have been most interesting. They are:

A firmly established record of the existence of line-to-line disturbances in addition to those disturbances usually considered in lightning arrester operation. These disturbances were found to be taking place during "uneventful" periods of operation, with nothing to show from the general indications why they had happened.

Evidence, also positive, that line-to-line phenomena apparently act like static line disturbance, both "slowly" and "suddenly". This was evidenced by getting punctures in the shunt-gap papers of the low-equivalent alternating-current

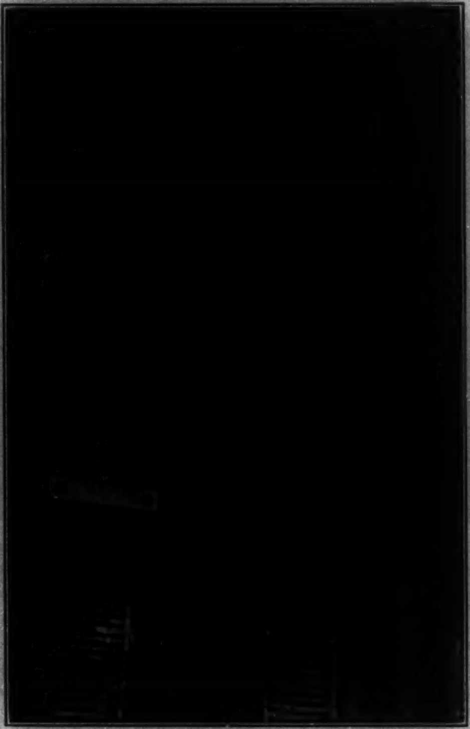


Fig. 5.—Presumpscot Electric Co. Interior of Eel Weir half-way line lightning arrester house

arrester line-to-line equipment at Eel Weir Power Station. In another case the resistances of the low-equivalent arresters used for line-to-line protection were fused. To do this, means a potential that could hold long enough over the series gaps and shunt and series resistances in series to fuse the wire. This was, however, a rare occurrence.

Indications existed that line accidents, such as the wind blowing the wires together, will cause a wave of phase-to-phase disturbance to travel a long distance and operate the line-to-line protection; that on the closely adjusted gap sets the fuses invariably blew; and that some line-to-line action nearly always accompanied line-to-ground operation.

FIG. 6.—Presumpscot Electric Co. Eel Weir Falls power station

Just above basement windows, over the tail-race, special ground connections of broad copper straps may be seen. These lead off in two separate directions to additional grounds in order to assure good operation of the protective apparatus. The original ground is in the tail-race.

A tabulation added hereto shows the relative number of times, etc., this apparatus operated. From this I feel safe in drawing two conclusions: first, that proper line-to-line protection is as essential as line-to-ground protection. Thus confirming Wirt's contention.* Secondly, that the line-to-line operation is likely to take relatively considerable time, and, therefore, that in the long run high and stable resistance in the discharge

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* A.I.E.E PROCEEDINGS, Vol. XXIII, p. 558.

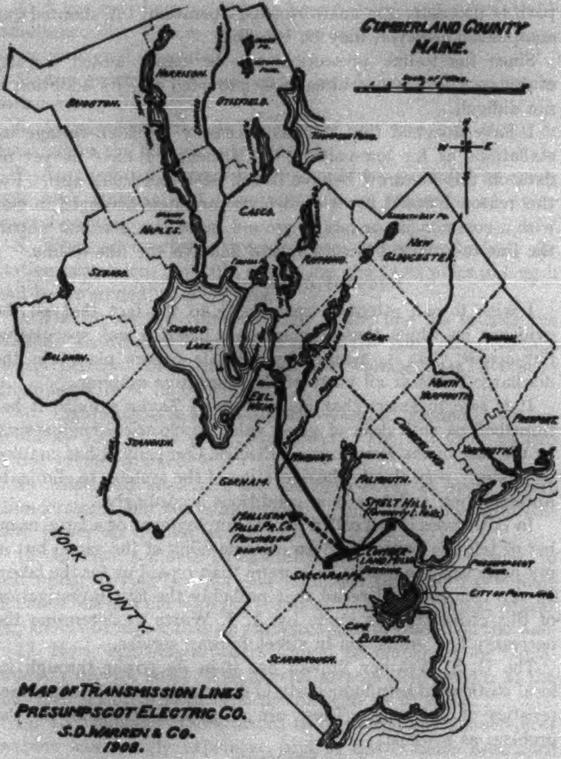
CUMBERLAND COUNTY
MAINE.
HARRISON.
BRIDGTON.
OTISFIELD.
THOMPSON POND.
W
E
CASCO.
NAPLES.
SEBAGO.
RAYMOND.
SABBATH DAY PD.
NEW GLOUCESTER.
SEBAGO LAKE.
GRAY.
BALDWIN.
POWNAL.
NORTH YARMOUTH.
EEL WEIR.
FREEPORT.
STANDISH.
CUMBERLAND.
YARMOUTH.
WINDHAM.
GORHAM.
FALMOUTH.
SMELT HILL.
MALLISON FALLS PR. CO.
(Purchased power)
CUMBERLAND MILLS DIVISION
SACCARAPPA.
PRESUMPSCOT RIVER.
CITY OF PORTLAND.
YORK COUNTY.
CAPE ELIZABETH.
SCARBOROUGH.
MAP OF TRANSMISSION LINES
PRESUMPSCOT ELECTRIC CO.
S.D. WARREN & CO.
1908.

FIG. 7

Presumpscot River is one of the most interesting as well as one of the best water-power streams of its size in the United States. It is the outlet of Sebago Lake, which lies about 17 miles northwest of Portland. The lake is fed by Crooked River, a stream heading 35 miles farther north and within 3 miles of the Androscoggin. The area of the lake is 46 square miles; the total water surface on the drainage basin is 97 square miles; the area of the drainage basin at the outlet of the lake is 420 square miles, and at the mouth of the river 600 square miles. According to the survey made by Joseph A. Warren, of Cumberland Mills, the fall from the crest of the stone dam at the foot of Sebago Lake to mean low tide at the foot of the lower falls is 265.16 feet in a distance of 21.65 miles, or an average of 12.25 feet per mile.—*From U. S. G. S. Water Supply Paper. No.* 201, *p.* 72.

path is necessary for uninterrupted operation. A shunted-gap equipment, however, may be valuable.

Since line-to-line protection can be easily added to any multigap arresters not already so provided for, its adoption is not difficult.

I have assumed that it is as necessary for high-voltage installations as for low-voltage, for although I have as yet no data on this feature I believe it will be found there also. For this reason I would favor electrolytic arresters arranged in star with a common jar or jars to ground, since this does not impair the line-to-ground protection, and adds to the line-to-line.

## RECORDS OF OPERATION

I wish to call attention specifically to the fact that all the evidence on which these remarks are based is not speculative but *actual*; that is, assured by tell-tale papers placed in the discharge paths at all parts of the respective systems.

It is safe to assert that in the case of Taylor's Falls, it has furnished us with data of great value to electrical engineering. In the case of the Presumpscot Electric Company it has enabled us to study very closely the operation of the system, to eliminate uncertainties, and to adjust conditions accordingly.

In both cases it has called for the employment of a large number of tell-tale papers, and an irksome filing of the same, but in my judgment the results have more than repaid us for the labor. In this connection, I recall that probably the first investigation of this character was made by A. J. Wurts to determine the necessary line protection in street railway service.

The U. S. Weather Bureau has it in its power through its local stations to help immensely in determining the local characteristics of lightning. These are of great importance to the problem as a whole.

## SUMMARY

As a result of the studies in lightning phenomena on Taylor's Falls and Presumpscot Electric Company's circuits, herein discussed, I would add the following summary on this subject.

*Line disturbance by lightning.*

1. Lightning disturbances on a line are more than likely to be local varying approximately from 1000 ft. or less, to several miles. The longer areas being less frequent.

2. They are likely to happen at any part of the line.

3. A direct stroke of lightning is not necessarily harmful: it depends upon the quality of the stroke, etc.

4. A line may be affected by a bound charge and direct stroke simultaneously. There is as yet no evidence to enable these to be measured separately.

5. Any grounded wire suspended on the line will tend to absorb a charge.

6. An overhead grounded system of one wire, two wires, or more, *above* the line wires is desirable.

7. An overhead grounded wire should be grounded at every pole near stations and important places, otherwise at every several poles.

8. When an overhead grounded wire is used exclusively for station protection, it should not be less than two miles in length and be grounded at every pole.

9. The higher the voltage design of the line the greater the possible disturbance from lightning to the line. High-voltage lines, therefore, need, more than low voltage ones, overhead grounded wire or its equivalent.

10. Lightning-rods added to the overhead grounded system probably add to the protective power. The full value of this is not yet determined.

11. Shattered insulators are liable to occur in every severe thunderstorm, but not in light ones. Puncture is more probable with power on the line at the time.

12. Insulators should be carefully selected for the service, to test under driving rain not less than two times normal voltage between line and pin with pin grounded. The equivalent spark-gap should be higher than any arrester path to ground on the line.

13. Horn lightning-arresters should be employed for extraordinary service only. The general arrangement known as the multigap selective path type promises to be of value.

14. Lightning-arrester stations to discharge line disturbances become increasingly expensive, and of questionable assistance the higher the voltage transmitted. Their total number depends on the length of line.

15. Wood poles may be effectively protected against splintering from lightning discharge by providing them with a small metallic conductor to ground.

*Station protection.*

17. Electrolytic lightning-arresters have so far behaved creditably, particularly in sensitive relief of grounds, but do not indicate a complete superiority over other types.

18. Line-to-line protection is desirable.

19. Apparently there cannot be too much protection on a plant. Every lightning-arrester added plays a part, but *practically* there is a limit. For many reasons it is obviously desirable to keep the station protection as simple as possible. It is, as yet, impossible to define what this should be.

20. If a full measure of line protection is added, such as overhead grounded wires, the stations will, in turn, be much relieved.

*General.*

21. Further and fuller data are required on the following:

*a.* Amount of direct stroke actually encountered on transmission lines.

*b.* Magnitude of bound charge possible on any given line—graded according to design—voltage.

*c.* Effect of line impedance to travel of static disturbance.

*d.* Corroborative data of the effectiveness of overhead grounded wires.

*e.* The relative value of overhead grounded wire for wood pole lines of short spans as against steel-tower lines of long spans.

*f.* Best relative position between overhead grounded wire and line wires.

*g.* Relative value of one, two, or three, etc., grounded wires.

*h.* Best relative position for lightning-rods.

*i.* Action of insulators under direct stroke.

*k.* Equivalent spark gap of high-tension insulators.

*l.* Relations between shunt resistance and given opening of horn gap.

*m.* Nature of line-to-line disturbances on very high voltage systems.

*n.* Equivalent spark gap of line choke-coils and consequent protective power.

## APPENDIX

## LIGHTNING PERFORMANCE DATA, SEASON 1907. PRESUMPSCOT ELECTRIC COMPANY, WESTBROOK, MAINE

*Summary.*

Length of record, approximately, 26 weeks, June to December, 1907.
Number of changes to tell-tale papers 30 complete.
4 part changes (local).

| Attending circumstances | Lightning | Clear* | Switching | Grounds and short circuits | Total |
|---|---|---|---|---|---|
| Number times disturbance occurred to lightning protective apparatus........ | 10 | 9 | 2 | 4 | 25 |

* Includes all other weather but lightning; causes not known, usually light discharges over some isolated unit; for example, phase to phase.

*Distribution of Operation.*

Two-phase. 2300 volts. Lightning protective apparatus.

| Date | Line to ground % | | Phase to phase % | |
|---|---|---|---|---|
| | Total = 18 paths | | Total = 9 paths | |
| 6/23-26 | | 22.2 | | 22.2 |
| | Total = 22 paths | | Total = 11 paths | |
| 6/26-27 | | 72.6 | | 45.4 |
| 7/21-27 | | 9.08 | | 11.1 |
| 7/27-8/3 | | 4.54 | | 11.1 |
| Average—per wk. for 26 weeks | | 4.18 | | 3.45 |
| " per disturbance.... | (4) | 27.11 | (4) | 22.45 |

NOTE: Figures given equal percentage of total protective apparatus paths operating.

Three-phase. 11,000 volts. Lightning protective apparatus.

| Date | Line to ground % | | Line to line % | |
|---|---|---|---|---|
| | Total (paths) = 33 | | Total = 15 | |
| 6/18-19 | " | 9.1 | | 46.6 |
| 6/23-26 | " = 39 | 48.8 | | 87. |
| 6/26-27 | " = 33 | 54.8 | | 73.2 |
| 7/7 - 8 | " = 39 | 33.3 | | 46.7 |
| 7/8 - 9 | | 59.1 | | 33.3 |
| 7/14-21 | | 7.7 | | 20.0 |
| 7/21-28 | " = 42 | 40.4 | " = 18 | 77.8 |
| 7/28-8/4 | | 71.5 | | 94.6 |
| 8/25-9/1 | | | | 11.1 |
| 9/1 -15 | | | | 11.1 |
| 9/15-22 | | 14.3 | | 33.3 |
| 9/22-29 | | 50.0 | | 78.0 |
| 9/30-10/6 | | 2.38 | " = 15 | 40.0 |
| 10/6 -13 | | | " = 18 | 11.1 |
| 10/20-27 | | | | 16.7 |
| 10/27-11/3 | | 4.76 | | 11.1 |
| 11/3 -10 | | 9.52 | | 50.0 |
| 12/1 - 8 | | | | 5.55 |
| 12/8 -15 | Special by switching | 35.8 | " = 12 | 75.0 |
| Average per wk. for 26 wks. | | 17.0 | | 31.7 |
| Average per disturbance | (14) | 31.5 | (19) | 43.3 |

NOTE: Figures given equal percentage of total protective apparatus discharge paths operating.

*Prominent characteristics brought out.*

1. Line-to-line disturbances pronounced, and of greater frequency than line-to-ground disturbances.

2. Line-to-ground, freer over fuses in shunt to low-equivalent, but this does not prevent the low equivalent operating at the same time.

3. Circuit-breakers set too light, objectionable; open on blowing of fuses, disturbing the balance of the system, and then frequently causing a loss of power while stations are getting into synchronism again.

*Operation of power plants.*

The Presumpscot Electric Company is not always able to operate to the best advantage electrically, because of the conditions which obtain. In the first place, the flow of water must be maintained primarily for the interest of the direct development of the mill at Cumberland Mills. Again, all the hydroelectric stations are on the same river, and while the flow of this is controlled, the company must, of course, protect the other users on the river. This introduces another variable. Furthermore, the supply of water to Saccarappa and Smelt Hill stations is affected by the run-off from the territory between the lake and the sea on which the streams are not ponded. It becomes evident, then, that during heavy rains, or in the spring, when there is a large amount of side-stream water, the flow from the lake may be well cut back, and Eel Weir is then unable to furnish its full supply. On the other hand, if the electric station below calls for water, more water must be run through the Eel Weir station than is desirable. In order to furnish a uniform flow at Cumberland Mills, it is sometimes necessary to store in the Saccarappa pond, and again to sluice, thus producing a variable head.

There are a number of other conditions which have a greater or less effect upon the system, and it is to harmonize all these that the company maintains turbo-generators, always having one floating on the line prepared to make good any little deficiencies, and the other two are usually warmed up ready to run, so that whatever the demands of the paper mill, they can be met up to the limit of the water power at that moment available, plus the turbine. If the load exceeds that, steam engines must then be substituted for motors on some of the large groups in the mill.

## DISCUSSION ON "COMPARATIVE TESTS OF LIGHTNING PROTECTION DEVICES ON THE TAYLOR'S FALLS TRANSMISSION SYSTEM", AND "STUDIES IN LIGHTNING PERFORMANCE, SEASON 1907." NEW YORK, MAY 19, 1908

**H. W. Buck:** The valuable data presented to-night include the most comprehensive and systematic record of lightning disturbances which has been presented to this Institute. In the old days of electrical transmission most of the trouble we had to cope with was due to the station apparatus itself, as the insulation of the lines was relatively high. As line voltages have risen with the progress of the art, the insulation of station apparatus has risen in proportion. Presumably lightning stresses have remained constant, so that at the present time we have insulation in our stations which perhaps on the high-voltage transmissions is high enough to withstand the original lightning surges, and the troubles seem to be shifting out upon the line itself. I think that this is the most noticeable feature of this paper. During the storms spoken of in the paper, many insulators were shattered, poles were shattered, and some cross-arms burned, and so on, and yet only one transformer bushing was damaged within the station.

It has conclusively been shown that these line troubles have been reduced by means of the overhead ground-wire. It is shown not only in this particular system, upon which we have the record to-night, but the experience over all this country with transmission lines, where the overhead ground-wire has been installed, shows similar corroborative evidence. There are perhaps three functions of this overhead ground-wire: it takes the direct stroke and it allows the induced charge to accumulate on the ground-wire instead of accumulating upon the transmission wire itself, so that when the cloud which induced this charge discharges itself through a lightning flash the corresponding charge of opposite polarity on the ground-wire can discharge itself through the ground connections on the pole, instead of having to spill over the insulators. Another important function of this overhead ground-wire consists in shielding the transmission wires from induced potentials between phases, due to neighboring lightning discharges, which are presumably of high frequency. The guard-wire forms one side of the circuit and the ground the other, so that we really have a short-circuited shield against induction on the transmission wires—the ground and the shield-wire being connected by electrical connections. If this theory be correct, it would seem to be a decided advantage to have two overhead ground-wires rather than one, a connection being made between these two shield-wires at every pole. Then we should have a shielding effect in the vertical plane and also in the horizontal plane against induced potentials, between the phases in the transmission wires. These short-circuited loops in fairly close proximity to the transmission wires might represent some induced loss on the normal frequency of the transmission system, but I doubt if it would be enough to be very serious; whereas at the frequency of the lightning discharge the possible induced current might be high and give a decided shielding effect to the transmission wires.

The evidence of the spilling over of accumulated charge in the insulators seems to show that the actual magnitude of the momentary current in this ground-wire is very large. I think it would be interesting if some form of current-recording device could be installed experimentally in some of these guard-wires, in order to give an indication of the magnitude of the currents. It would seem that along transmission lines there might be installed in circuit with the guard-wire a crude form of ballistic galvanometer, which would give a record of the maximum current flowing in the guard-wire during a storm. It would tend to indicate what conductivity ought to be established in these shield-wires to take care of discharges, and would give valuable records.

It is quite noticeable from the records of this paper that lightning storms follow certain well-defined paths throughout a region. There seem to be certain sections of the line which have borne the brunt of the lightning discharges; whereas other sections of the line have been practically free from trouble. I think that this accords with the experience of the Weather Bureau, in showing that lightning storms tend to progress along certain well-defined topographical paths. The frequent shattering of insulators as shown in these records indicates the desirability of developing some form of insulator which can withstand such a stress. The problem is a mechanical one, to get some material that can withstand the sudden application of the heat of an arc without it resulting in the insulator being shattered. It is not so bad to have a momentary short-circuit on a system, provided it blows itself out and leaves the insulator in comparatively good condition, but if every time a spill-over takes place the insulator is going to be destroyed, the operative difficulty becomes a serious one.

The horn arrester seems to have assumed a very important function in coping with the lightning problem. It is cheap and easy to insulate, and it can be put out of doors and withstand heavy rains without the insulation being impaired. It can also withstand very violent fireworks without the destruction of any valuable apparatus. In conjunction with the development of the horn arrester the problem of a good form of resistance is brought up. It seems to me that no really satisfactory form of resistance has yet been developed. The water rheostat is satisfactory under some conditions, but it is bulky, and in cold weather there is trouble from freezing. A resistance ought to be developed which can withstand frequent discharges and which can carry without destruction, for periods of several consecutive seconds, a large dynamic current from the generators. With a resistance of this kind, sufficient surge current could flow to ground without necessarily shutting down the system.

It is interesting to note in this paper that certain discharges have been noticed on the secondaries of the transformers. This accords with my experience and with that of other engineers with whom I have talked. I have known of several instances where overhead lines pass through transformers into underground cable systems, where cable punctures have resulted simultaneously with thunder storms along the overhead lines. This indicates a possible necessity for having lightning-arresters of some form on the secondaries as well as on the primaries of the transformers. I have noticed in the Taylor's Falls installation that there are such static dischargers on the secondary circuits.

It is also interesting to note that the tell-tale papers in shunt with the test choke-coils on the line have been punctured. This certainly indicates that choke-coils act as barriers to the progress of these lightning surges in spite of the fact that this has been disputed so many times. It is evident that choke-coils are a decided protection where they are installed.

In general, I believe that with steel construction adopted throughout a transmission line so as to eliminate the burning and shattering experienced in wooden construction, and with one or more guard-wires installed along the line and over the transmission wires, that most of the serious lightning troubles on overhead lines will be eliminated.

**P. M. Lincoln:** In Figs. 11 and 12, Mr. Vaughan shows a number of curves the ordinates of which purport to give the static stress upon the insulators. I am not convinced that they do represent stress on those insulators. The ordinates of these curves are taken as the diameters of holes which were punctured in the tell-tale papers, and from that diameter is deduced the stress upon the insulators. I doubt if the diameter of a puncture in the tell-tale paper is an indication of stress on the insulator; I think it an indication of the current that has passed through that tell-tale paper. The current may have come from a lightning stroke, but more likely it has come from the passage of the dynamic current.

**J. F. Vaughan:** The question of interpretation and graphic representation of these tell-tale papers is open to discussion. It has been given a good deal of thought in the preparation of the curves. The curves are drawn up to show graphically or pictorially the differences in stress on the insulators, spill-overs of static and dynamic discharges; and the scale assumed in plotting the curves is intentionally exaggerated in the lower ranges to facilitate comparison of the smaller punctures. The curves should be interpreted in the liberal spirit in which they were plotted; that is, as a general indication (as accurate as possible) of the relative activity of disturbances in each case.

**P. H. Thomas:** These papers differ from most lightning-arrester papers in that they are a simple record of practical operating results and not a compilation of theories. What is most needed in the study of the lightning problem is not so much theory and speculation as sufficient data and knowledge as to exactly how lightning affects a transmission line, so that an intelligent design can be made of protective apparatus, and so that the action of such apparatus can be properly judged. These papers go a long way toward showing the nature of the attack of lightning on the high-tension transmission line. Of course the data here recorded are not necessarily typical of all lines, but they indicate in a general way what may be expected to happen.

The interpretation of these punctures in the tell-tale papers is important. It will be found on examining the data that one storm occurred when no generator potential was on the line at all; in another case the potential went off in the early part of the storm. In these storms, then, at least during the major part of them, there was no actual generator potential on the line. The punctures in the tell-tale papers were just as severe during the times when there was no generator connected with the line as at any other time. Most of the punctures show, on examination, that the fibres of the paper are unburned even when large holes appear, showing them to be purely static discharges. In other words, the holes in the punctured papers are simple records of the static passing over the line.

I have not counted the total number of so-called spill-overs, but there must be hundreds of them. These are cases where a static discharge has passed over the wire to the pin from the surface of the insulators and not a capacity current to the pin. Only a small percentage of these spill-overs have injured insulators.

It is interesting to know that there has been very little disturbance of any serious character at the stations. Mr. Buck draws the conclusion that it is because the insulation of the station apparatus has been raised in relation to that of the line. It seems to me that the reason for the relative immunity of the stations is that the action is entirely local, the attack of the discharge being so sudden that it cannot pass more than a very short distance along the line. It is not of sufficient energy to cause any very great disturbance unless it should start an arc from the generator. It has been frequently assumed that the high potential on the line wire, due to lightning, is the release of a charge. This may be true, but I think the evidence points the other way. This is a matter which ought to be studied. The evidence suggests more strongly, it seems to me, the direct jumping to the line wire of electrical energy direct from the atmosphere and not the drawing of the charge from the ground.

**V. E. Goodwin:** The papers presented this evening are of special interest to me as I lived several years in Minneapolis and am quite familiar with the nature and severity of the lightning storms in that vicinity. I also inspected the Taylor's Falls system with Messrs. Vaughan and Neall during the preliminary testing of the line and protective devices. I was then of the opinion that it would be difficult to draw definite conclusions from the results they would obtain, as the system was so completely equipped that it would be impossible to differentiate the protective values of the various devices. I now believe that the papers presented to-night show conclusively that reliable data have at last been obtained on the effects of lightning on a transmission system and on the relative values of various types of overhead ground-wires.

The phenomenon regarding direct strokes of lightning on transmission lines mentioned by Mr. Vaughan has been reported on several other systems. One would naturally think that a line would be more subject to direct strokes after the wires are up than before. It seems probable that where the wires are up the charge dissipates over several insulators and poles and therefore does not splinter or burn the poles. I therefore question the ability of an investigator to determine from tell-tale papers whether a disturbance results from a direct or induced stroke of lightning.

The magnitude and intensity of many of the strokes indicated in these records give us a good idea as to what is required of a station lightning-arrester. The records indicate that the station arrester did not have sufficient discharge rate to relieve the line at those points, thus causing the horn arrester, which had a higher breakdown point, to discharge. In designing the latest types of arresters great care has been taken to avoid all series resistance and to increase the discharge rates. This feature has been thoroughly carried out in the aluminum type electrolytic arrester, by the use of large plate area and an electrolyte of very low specific resistance, thus giving low internal resistance and a maximum discharge ability.

It is interesting to note that many of the induced strokes on the Taylor's Falls line were highly concentrated and often of great intensity and volume. This is indicated by the storm of July 4, where one puncture 1.75 in. in diameter was recorded. The absolute protection of a line under such conditions becomes a very difficult problem. It is evident that one or two overhead ground-wires are of considerable assistance in shielding the line wires, but at best they can only be of partial protective value. The problem of a line-type lightning-arrester for this purpose involves the installation of several arresters per mile, and this, of course, is prohibitive in any transmission line of over 2300 volts. The only case where such arresters can economically be installed is at an exposed point, where experience indicates that the expense is warranted.

The Taylor's Falls tests indicate that during every storm a great many insulators spilled over without any resultant damage to the insulators or interruption to the service. I believe that the only means of entirely protecting an overhead power circuit lies in the development of an insulator which will not puncture, and, while having a fairly low spill-over, will not shatter. This perfection in the petticoat type of insulator is probably out of the question, but I believe it can be attained by a properly designed and proportioned insulator of the suspension or strain type. Such an insulator would be the equivalent of a line arrester at each pole or tower on the line.

**E. E. F. Creighton:** The two additional subjects I wish to discuss are the interpretation of tell-tale papers and the use of resistance type of horn arresters. The conditions which muddle the tell-tale records are: first, the impression of several static discharges on each paper before they are removed; secondly, the complete destruction of the static puncture holes by dynamic current. A fraction of an ampere of dynamic current for a half cycle of the generator wave is sufficient to destroy the static record. The authors were fortunate in obtaining records on an idle line. It may be suggested to those who are willing to aid in collecting data on this subject that the only data of great value in the study of lightning potential should be taken on an idle line, and furthermore should be collected on moving tapes by clockwork so as to separate the punctures due to each cloud discharge.

The value of the resistance type of horn arrester for discharging lightning increases as the value of series resistance decreases. On the other hand, the disturbance that one of these arresters may cause on the line increases as the series resistance is diminished. The menace resulting from a discharge through one of these arresters to ground may be either one of two effects, or both. First, the arrester may take sufficient current to overload the circuit-breaker. Opening switches under overload conditions should be avoided as much as possible, to say nothing of the interruption of service. Secondly, if the resistance is sufficient to prevent overloading, there may be a menace to the insulation by the operation of one phase only, especially on an insulated neutral system. It requires about one to two seconds at best for the arc to rise on the horns and go out. During this interval the arc varies from a short length to a very long length, and if there is a possibility of setting up a surge on the system this arc is most likely to produce the condition. On any particular system these arcs may occur repeatedly with impunity, whereas on another system the surge conditions will be such as to cause a destruction of apparatus on some other part of the system. To illustrate this two examples are cited:

On a 17,000-volt, 60-cycle, delta-connected system a single gap in series with enough resistance to limit the current to 0.5 ampere was connected between line and ground. Even with this high resistance all five of the arresters in the station on three feeders discharged continuously so long as the arc played across the gap to ground. A lightning-arrester of so limited a discharge would have little practical value, yet the surges caused by the discharge assumed dangerously high values.

As a second example, it is a common occurrence on cable systems to have several failures of cables after one has taken place, due probably to the surges set up during the first failure.

If one goes back over the history of the use of horn gaps with series resistance, he will find the hope always held out that an operator will finally obtain the right adjustment of resistance to give excellent protection without a resulting interruption of service. This has never been accomplished, and I think it can be shown that it never will be.

If we did not have the aluminum arrester it would be worth while working out the best conditions for the resistance horn-gap arrester. A comparison of the two will show the limitation of the resistance horn type and the uselessness of the development. At 60,000 volts every ampere of discharge through the series resistance of the horn gap represents, roughly, 60 kw. per phase, or 180 kw. If an arrester will not discharge 100 amperes, I think it will not take the usual run of heavy discharges. With this rated discharge the generator would be called upon to furnish 18,000 kw. On the other hand, if an aluminum arrester is used, the energy taken from the generator will be less than 20 kw. and the rate of discharge of lightning will be several hundred amperes at the same abnormal value of potential. The valve action of the aluminum arrester prevents almost entirely the flow of dynamic current at normal potentials and has a free discharge only at abnormal potentials. This information is sufficient to show the futility of using the resistance type of horn-gap arrester.

Furthermore, the current taken by the aluminum arrester from one phase to ground is leading, the same as the capacity current of the line or cable, and consequently one phase may arc continuously between line and ground without setting up high surges on the system. It should be noted that the aluminum arrester actually maintains the voltage and thus prevents grounding the line conductor.

**President Stott:** In listening to the discussion, I recall the experience of eleven years ago with the Niagara transmission lines. I am not certain whether this was the first line equipped with overhead ground-wire, but at all events it was so equipped when it started. After a few months' experience with the overhead ground-wires it was decided to take them down, as in the choice of two evils the lesser one seemed then to be the troubles due to lightning. This was due to poor material in the ground-wires themselves, as they were continually breaking and short-circuiting the lines. Now eleven years after, we hear that as the result of a most elaborate series of tests and investigations the ground-wire gives the most certain protection. In a practical way there is every reason why it should. No one ever heard anywhere of an underground cable being struck by lightning. That means that if the ground itself is above the conductor the line is safe. We cannot possibly afford to put all transmission lines underground. A 60,000-volt underground transmission line 200 miles long is absolutely impossible from a financial or commercial standpoint; but instead of putting the wires underground, we can in effect put the ground above the wires. The most perfect protection will be got where we have the most perfect network of ground-wires above our conductors. I think everything said to-night points to that fact.

Now to avoid ordinary troubles there must be a high factor of safety in all apparatus. Troubles with underground cables are almost unknown outside of mechanical damage and faulty joints, and the reason is that those cables are made with an extremely high factor of safety; for instantaneous voltage it is five; for continuous service, two. Just as it is with a human being, if a man is in a weakened condition every few germs that come along will give him a new disease; but if he is strong enough they won't affect him at all. We have got to make our system germ-proof, as it were, and have a very large factor of safety on the insulators. That, and the ground-wire, I think, is going to be the solution of our overhead transmission work.

**J. F. Vaughan:** I am sorry not to hear more discussion on the interpretation of tell-tale papers, as there is plenty of material for discussion. It is rather surprising that with the necessarily crude methods of measurement used there are not more apparent inconsistencies in the results. For instance, the three wires grounding the three pole pins through individual tell-tale spark-gaps are not more than a few inches apart and are mounted on porcelain knobs only, which might be expected to allow disturbances of such intensity as have been indicated by the papers to break across from wire to wire. This fact brings out one point which has not been touched on, and that is the lack of pronounced phase-to-phase disturbance, indicating that the main stresses which are between wires and ground do not greatly differ in the three wires.

**N. J. Neall:** I wish to emphasize again the points which I have made about insulators. According to the theory which I have advanced in my paper, suspended-type insulators would be subjected by lightning to greater disturbance locally than any insulator so far used for lower voltages, because I am assuming that there is no special overhead protection at all, and am taking the broad case. If the transmission wire takes this lightning charge, the charge must get to the ground some way or other, and the only place at which it could do so would be presumably by way of the insulator support. The suspended type insulator has not come into the Taylor's Falls problem, and we have no data respecting it; but if insulators could be studied with reference to the equivalent spark-gap we would probably find certain explanations of the phenomenon at which we can now only guess. I think that is a point on which the Institute should have the fullest possible information, if not from a practical reason, certainly in connection with the advancement of the art, and, perhaps, indirectly, of the science.

**V. D. Moody** (by letter): In a paper presented at a recent meeting of the Institute,* Messrs. Rushmore and Dubois recommended for insulator protection steel rods with ends pointed, bolted to the vertical members of the towers and projecting above the highest point of the line. This method of protection was freely criticized, but my experience is that this type of arrester is highly valuable.

Several years ago this type of arrester was used on the Winnipeg hydroelectric installation at Winnipeg, Canada. The transmission line was 65 miles long, delivering about 20,000 h.p. at 60,000 volts, 60 cycles. From the power house to the substation duplicate transmission lines of No. 00 B. & S. hard-drawn cable, with a hemp centre, were run in duplicate on steel towers. This line crosses the Winnipeg River with a span of about 760 ft., on towers 72 ft. high, each weighing about 6 tons, with a sag in the line of about 23 ft. at 50 degrees. The standard towers are 40 ft. high, weighing about 2400 lb., spaced 500 ft. apart with a sag of about 14 ft. at 50 degrees. There are four railroad crossings. At Winnipeg, this line crosses the Red River with a 1100-ft. span, the towers are 105 ft. high with a line sag of 45 ft. at 50 degrees. These towers weigh 15 tons. The railway and river crossing towers are on concrete footings, and are grounded with a ground-plate. This transmission line has 10 complete transposition spirals and is paralleled by a telephone line of No. 8 B. & S. hard-drawn copper wire on porcelain insulators on the towers. The telephone line was transposed at each tower. The telephone line and transmission line insulators were made of the same kind of porcelain.

On all of these towers this steel-rod type of horn arrester was used. In operation it was found that the protection afforded was extremely valuable, as none of the high-tension insulators was punctured in several very severe lightning storms. In this country the storms are very severe in the summer months. In one instance five miles of telephone line was knocked down and insulators broken without breaking any of the line insulators, although the effects of the storm were felt in the sub-station by throwing out of synchronism, momentarily, the 800 kw. motor-generator sets.

This line has now been in operation since June 1906, and has never had a shutdown. As the storms have been severe, I feel assured that these arresters are doing good work, as this is the only protection on this line.

It appears to me, that this type of arrester with a ground-wire and multigap station arresters with choke-coils will afford protection that can be relied upon.

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* TRANSACTIONS A. I. E. E., Vol. XXVI, page 425.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29, 1908.*

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# THE EVOLUTION OF ENGINEERING

## PRESIDENT'S ADDRESS

BY HENRY GORDON STOTT

Eighty years ago Thomas Tredgold defined engineering as "The art of directing the great sources of power in nature for the use and convenience of man." Progress in engineering has been greater in the eighty years which have elapsed since this definition was made than in the previous period of 4500 years beginning with the first great, tangible piece of engineering, the pyramid Cheops.

The question naturally arises: does this definition hold good to-day? Is it broad enough? If not, how can we better define the engineer's sphere of activity? If we accept Tredgold's definition as our standard, will we reach the position in society which belongs to us by right of education, achievement, and highly developed power of logical deduction from facts observed and investigated?

Engineers may be divided into two general classes: first, those who believe that the engineer should be restricted to a specific vocation, such as electrical, steam, hydraulic, pneumatic, or sanitary engineering, etc; second, those who wish to see him take his place not only as an engineer but also as a public-spirited citizen and leader.

The great amount of specialization which obtains in electrical engineering to-day is instanced in the subdivisions now found, such as telegraphy, submarine telegraphy, telephony, wireless telegraphy, railway signaling, underground cable engineering, high-tension transmission, electric lighting, electric railways, alternating-current generator designing, direct-current generator designing, railway motor designing, converter designing, transformer designing, railway, lighting, telegraph, and telephone switchboard engineering, etc.

The score or more of divisions of electrical engineering which exist to-day are the necessary outcome of the consolidations of manufacturing and other interests into a few large concerns: they are the natural economic results of competition. As these consolidations have undoubtedly resulted in greater efficiency and, therefore, in reduced cost of production, there is every reason to expect a continuance of this evolution from the simple factory manufacturing only one article, to the complex one which manufactures many things. In such a factory it is manifest that as soon as any one article is called for in sufficient quantities to require the entire time of the man in charge, a new department will be formed and another subdivision of engineering created. In exactly the same way we will find consulting engineers who specialize on cables only, others on illumination, etc., and on any pursuit which is of sufficient importance to claim undivided attention. This process of segregation is evidently one of infinite application in all pursuits, tending strongly to an ever narrower development of the individual, but at the same time increasing his efficiency to a maximum in his own particular specialty. This increase in efficiency, however, will cease if the engineer becomes so highly specialized as to ignore the necessity of keeping in touch with the entire sphere covered by his company, as the evolution of each branch must be synchronized with that of all.

The other class, to which the term "second" has been arbitrarily assigned merely to indicate its numerical inferiority, embraces all those who have broadened their field through self-education, experience, opportunity, and natural adaptability for administrative work. The term self-education is used advisedly, as both classes are assumed to start with the same technical training, and as a matter of actual fact the second class almost invariably evolves from the specialists.

The engineer who is called upon to report on a projected railroad, for example, must also be a student of political economy in order to give proper weight to the various economic problems which must be first studied before he reports upon the advisability of even making a survey. He should be thoroughly familiar with the general organization of the state governments through whose territory the road may run, as well as have a general knowledge of their laws affecting corporations, franchises, etc. In order efficiently to carry out his work, it will be necessary for him to come in contact with various officers of the state and city governments, so that he should be a man of general and broad culture, capable of meeting anyone with credit to himself and the company he represents. Lastly, if he is personally acquainted with some of the more important state or city officials, or the members of the legislatu e, his work may be greatly facilitated and his services be just so much more valuable to his employer.

Tredgold's definition of engineering evidently did not contemplate this enlargement of the engineer's sphere, and it is only by a natural process of evolution that some have reached this stage.

The second class is necessarily a restricted one, as, whilst the legitimate field of work of the engineer is extremely broad and almost unlimited, yet as a rule he has apparently decided to keep in the background and only come to the front when called. The result of this policy is that when the opportunity comes, the engineer is taken at his own valuation and passed over for others who, whilst not suffering from modesty, are lacking in engineering education and experience, and therefore are forced to call in engineers (to act in a subordinate position) to supply the incumbent's deficiency in the qualifications necessary for the office.

A good illustration of this policy is furnished in the appointments made on two state public service commissions, in which the ten offices are filled by gentlemen whose occupations had been as follows; six lawyers, two manufacturers, one political office-holder, and one engineer. These commissioners have control of all matters pertaining to public service corporations; and as their functions are of an inquisitorial and critical character on subjects which are almost exclusively of an engineering nature, it is quite evident that their lack of engineering knowledge must be a severe handicap, not only to them but much more so to the state that employs them, and lastly, but not least, to the company or corporation suffering from their well-meant but misdirected efforts.

What is the cause of this anomalous situation. Is it entirely the fault of the executive who makes these appointments? Has not the whole body of engineers some share in the blame? We have seen that there is to-day an inherent tendency to specialization in engineering, and that by far the greater number of our members are becoming experts in one or two subjects only, and that comparatively few attempt to keep in touch with the more general aspects of engineering. This condition is caused not so much by a lack of willingness as by lack of time and opportunity.

This centrifugal force acting on our profession has fortunately a nearly equal centripetal one which is found in such societies as the American Institute of Electrical Engineers, by which all can once more be brought back to a common centre on the common ground so clearly described in our Constitution, which says that the object of the American Institute of Electrical Engineers "shall be the advancement of the theory and practice of Electrical Engineering and of the Allied Arts and Sciences."

The conference held in Washington, D. C., last month, which was called by President Roosevelt to consider what steps should be taken to conserve our natural resources, was preceded by a series of conferences held by the presidents of the four national engineering societies, at which a series of broad resolutions were drafted and afterwards presented at the conference as representing the opinions of 20,000 American Engineers.* The Committee on Resolutions presented a very able report to the conference, embodying practically everything we had recommended, with one exception, as that particular item had already been covered in a bill introduced into Congress. The resolutions were unanimously adopted.

Several important deductions may be made from this incident. First, united recommendations after careful investigations of facts by engineers, on any public question involving engineering problems, will be not only courteously received but welcomed and highly appreciated by our state and federal governments. Secondly, the facts presented at this conference were of such a far-reaching and important nature that every member of this Institute should feel it is his duty carefully to study the able papers presented, and to further in every way possible the policy of preserving our natural resources. In this we all can unite, no matter whether we are specialists or general engineers. Thirdly, coöperation on the part of the four national engineering societies is absolutely essential to success in any movement of this kind; and, as a corollary, success is certain if we coöperate. Fourthly, if engineers are to take the place in society which belongs to them by right of education and training, they must take an active part in matters of general policy or civic interest, no matter how remote these matters may seem from Tredgold's definition of engineering.

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* PROCEEDINGS A. I. E. E., June 1908, Section I, p. 5.

After nine of the ten commissioners' names previously referred to we can find the significant words, bracketed," active in politics. " Is there no lesson for engineers here? Is it not their civic duty to the state and nation to take a more active part in public affairs, giving of their special knowledge freely, as may be required of them, at the same time insisting upon the same high ideals of faithful, honest, and loyal performance of duties in public life as they have been accustomed to in their every-day work as engineers?

These suggestions are clearly outside the scope of this Institute as set forth in its Constitution, and in all probability would be pronounced heretical in any of our engineering societies, so that to carry them out it may become necessary to organize a new society in which membership would be limited to members of the four national engineering societies, and whose object would frankly be to use all legitimate political methods to influence legislation on matters affecting engineering; for example, such as carrying out the recommendations of the Conference on Preservation of Natural Resources, or the application of the principles of political economy to the laws affecting public utility commissions, etc.

An enormous amount of work must be done in order to induce our state and national legislatures to pass the necessary legislation in regard to preservation of our natural resources. No body of men is so peculiarly qualified to advise on these matters as that composed of engineers. Such a society could with propriety take up the consideration of many problems of which the public now hears only one side, and that usually the demagogue's, simply because the engineer has maintained an attitude of reserve. His silence is frequently mistaken for either assent or guilty knowledge, when in nine cases out of ten he remains silent either from a mistaken policy, dictated possibly by his employer, or because he considers it undignified to reply to criticism.

Belonging to a society whose object it is to guide and instruct public opinion in engineering matters, this feeling would soon disappear, and the benefit of coöperation among engineers in this respect would make this society's influence felt in every city and state in the country. Our large corporations and manufacturers are realizing as never before the benefit of publicity departments, not only for advertising purposes, but for the purpose of disarming adverse criticism by a calm statement of facts.

In conclusion, let us remember that if we wish to progress and assume our proper place in the world, we must be aggressive and not passive in allegiance to our engineering societies; that the day is long past for hiding our light under a bushel, and that instead of Tredgold's definition of engineering, the following more correctly expresses the position of the engineer to-day:

Engineering—The art of organizing and directing men, and of controlling the forces and materials of nature for the benefit of the human race.

## DISCUSSION ON "THE EVOLUTION OF ENGINEERING." ATLANTIC CITY, N. J., JUNE 29, 1908

**Charles F. Scott:** In the president's address reference is made to the part that the presidents of the national engineering societies played at the conference at Washington. One of the speakers referred to that conference as marking an era in American thought and American action. It seems to me it also may mark an era in the position the national engineering societies are to take as to public matters in general.

As a society, and as engineers, we may well congratulate ourselves on the part our president took in formulating the resolutions which were the formal outcome of that great and notable conference. It has been the ideal of many of us that the engineers of America, through their engineering societies, might get together for concerted action such as this. That was one of the ideas underlying the project in the Engineers' Building, and it is a happy outcome that so soon after it was opened, the founder societies have taken such an important part in this great national work.

The president's address admirably indicates the position which engineers should take in the future with regard to matters of this sort. The other papers this morning have been along the same lines, calling for the highest action, the coöperation of engineers, on a larger scale and in larger matters, and we can also congratulate ourselves that the new president, in sounding his keynote, has looked also to the broader and more useful development of the engineering society.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29, 1908.*

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# ELECTRICITY AS VIEWED BY THE INSURANCE ENGINEER; SHOULD THE A.I.E.E. INTEREST ITSELF IN FIRE PROTECTION?

BY C. M. GODDARD

If news had been received during the last six months of the total destruction of our fleet of battleships on its way to San Francisco, even without any loss of life, what a calamity it would have been considered, and how messages of sympathy would have poured in from all the governments in the world. The value of that fleet is probably less than $125,000,000; the property loss by the conflagration in the city of San Francisco, toward which that fleet was headed, of $350,000,000 by one fire, brought similar messages because it was an unusual occurrence.

The property loss by fire [in the U. S.] for the year 1907 was $180,000,000; the average annual loss for the last 32 years was $134,000,000; the national debt at its highest point was $2,845,000,000, or a little over two and three quarters billions; the insurance companies have paid $2,500,000,000 in losses since 1860; the total property loss by fire has been $4,250,000,000 since 1875.

There are approximately three hundred insurance companies doing business in this country, one thousand companies, or more than three times the present number, have failed or been retired since 1850. The three hundred companies have risks outstanding of over $30,000,000,000.

The annual number of fires in American cities averages 40 for each 10,000 of population as compared with 8 for each 10,000 population in European cities. The annual per capita loss in Austria, Denmark, France, Germany, Italy, and Switzerland varies from 12 cents in Italy to 49 cents in Germany, with an average of 33 cents as compared with $2.47 in the United States.

There is no question but that 50% of our fires are due to what we technically call "faults of management"; this includes all sorts of easily avoidable conditions that are likely to cause or aggravate fire hazard, a more common word would be "carelessness".

Just after the Collinwood School tragedy, a prominent metropolitan newspaper printed the following editorial on this unnecessary loss of life:

> A spasm of horrified emotion has passed over the country as a consequence of the deaths of a crowd of children in the fire which destroyed the Collinwood School at Cleveland. The horror is natural. It is a credit to the country. But the fire and its results were the natural effects of a succession of causes which discredit the country because they are characteristic of the country. The horror and the sympathy are human; they are common to all civilized communities; the recklessness which caused the unspeakable disaster is American. It has no counterpart elsewhere.
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> The city authorities, the school authorities, all were negligent. Behind their negligence stands the great, gaping negligence of the public, the same negligence that causes annually in the United States more accidental deaths and injuries than three great wars.
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> There is terrific loss of life and limb in this country from preventable causes. No other land shows anything like it, or anything approaching it. This is not because of the vastness of our population, but because of its carelessness. We are the most careless people on earth. We permit a looseness of conditions, a recklessness of method, or a method of recklessness which would not be tolerated in Great Britain or Germany or France. This laxity runs on our railroads, pervades our coal mines, meanders in our mills, asserts itself in the slovenliness of our cities and our vacant lots and is traced directly to our homes along the icy sidewalks to our front doors and the doors of our churches and public institutions. The average American cares no more about the conditions outside the walls of his home than he cares about the conditions on the most distant planet. We are indifferent and unashamed. The spasms of public horror are soon over and forgotten. They accomplish nothing.

This arraignment of the American people applies with equal force to our fire loss and ought to bring the blush of shame to every public spirited citizen.

You are familiar with the idea embraced in the first part of the title of this paper, "Electricity as viewed by the Insurance Engineer", but do not the foregoing facts and figures warrant the second part of that title and demand not only from the electrical engineer but also from all classes of business men a careful and thoughtful consideration of the subject of fire protection and fire prevention? Should not every member of this Institute join hands with his fellow members of the National Fire Protection Association, and do his part to stop this appalling destruction of accumulated wealth?

" A penny saved is a penny earned " and while the insurance or fire protection engineer cannot create wealth as do the electrical industries, he can endeavor to lessen the unnecessary destruction of created wealth and thereby prove his right to exist. We cannot fairly throw the whole burden of this work on the insurance companies, their profit would be the same if they did nothing to reduce the fire loss and simply made it a matter of rates.

This is true of every public service corporation, but you men know that your best efforts are given all the time to reducing the cost of production, not solely to increase your profits, but because your great desire is to please your customer by giving him better service at a constantly decreasing cost and with a reasonably remunerative profit for yourselves. Do you not believe that the insurance companies are actuated by just as reasonable, honest, and business-like principles?

The market of the stock exchange is known to be the most sensitive barometer of the financial condition of the country. The prospect of poor crops, and therefore a poor year for the railroads, will cause a drop in prices long before the failure of the crop is assured. Are you surprised that the underwriting interests are equally sensitive, when you consider that the combined capital of the American stock companies in 1906 was $60,000,000 and the insurance at risk was $22,000,000,000, that the net surplus of all American and foreign companies doing business in the United States was $147,000,000 and the insurance at risk was $30,000,000,000? A fire in the congested value district of New York covering an area equalling that of the San Francisco conflagration would wipe out of existence nearly every insurance company doing business in that city. Do you not see, then, that it is but natural for such interests to " view with alarm " every newly introduced agent that may affect unfavorably the fire loss? Do you not realize that when the simple act of a cow kicking over a kerosene oil lamp can result in a Chicago conflagration, that the hazard of kerosene oil lamps is a very different proposition from what it would be if such a careless act on the part of that cow could only result in the destruction of the lamp, or, at most, of the building in which the lamp is located?

What must the fire protection engineer know? There is only one answer—he must know something about almost everything, he must be versed in the construction of buildings, in their equipment with fire protective and fire productive devices; he must know the hazards of all the different manufacturing and mercantile occupancies of such buildings. How can a man familiarize himself with every known business? He cannot. That is why he comes to you for advice. His work must be largely critical and that is the reason he is unpopular. He comes to you and asks you to create, and then to submit your creation to him to criticize; and he tells you this or that feature is likely to produce a fire, so he will have to charge an admission fee if you add your creation to his existing risk. This is unpleasant for you and for him too. He has his own troubles without seeking a quarrel with you.

Cannot you work together? Of course you can. Trust him, you are honest; and he is equally entitled to be considered honest. Talk it over, find out how your pet creation can be changed so as to remain just as attractive to you and become unobjectionable to him. It is your duty as a patriotic citizen of this country to do all in your power to reduce the fire loss. Work with him for that reason and because it will be for your advantage; your assistance will be welcomed, even if your prime motive is not love of the critic or of the insurance companies by whom he is employed.

It is my intention in this paper to direct your attention to the work of the fire protection engineer in a little different light from what you might expect from the title; but you must remember that I am here now, not in my capacity as a member of this Institute but rather in that of a delegate from a sister engineering society, the National Fire Protection Association, a society of which this Institute is an active member. I am here to urge you to make that membership active, not only in name but also in fact, as far as you consistently can in connection with your other and regular professional duties.

I can probably never divorce myself in the minds of many of your members to whom I am personally known, from the insurance or underwriting interests, nor would I do so if I could; that is my life work and must claim my best efforts. In connection with that work, this Institute has, I am pleased to say, done able and efficient work, work that has been of great value to the underwriters, and, I firmly believe, of equal value to the great profession which you honor.

This is the first time that the National Fire Protection Association has been formally represented at an annual meeting of this Institute, and it seems to me that the time allotted to me in that capacity could not be better occupied than by endeavoring to show in a general way why there must be a close relation, either coöperative or antagonistic, between the electrical and the fire protection engineer. I could, of course, discuss some particular hazard or hazards of electricity as a fire producing agent, but if I can arouse in the membership of this Institute a sense of the duty they owe, not to the insurance companies but to mankind in general, so that each will give some thought and attention to electrical fire hazard problems, then we can trust to committees of conference to work out the details of each and all of the individual problems as they arise. Such work must always, in its results, be more or less of a compromise, often taking on a single point much more time than could be given here to the entire subject.

About fifteen years ago I suggested to some of the members of this Institute the desirability of active coöperation on the part of the Institute in the formulating of the underwriters' rules. But as this is, and should be a conservative body, it was not until 1896, in the National Conference, that the Institute itself took up this work, although many of its members had given valuable assistance from the outset.

You must admit that electricity may be a most serious fire hazard. The possibilities in that direction can hardly be estimated, and I believe that it was a most fortunate thing for the electrical interests that fire underwriters had begun to appreciate the necessity of fire protection before electricity was introduced for lighting and power, so that they immediately began to surround it with necessary and proper restrictions.

I think that no small part of the progress of your art has been due to the fact that in its early days, when the electrical engineer knew little about the fire hazard of electricity, the underwriter, knowing less but fearing much, appeared as an unwelcome but salutary obstructionist and at least caused the matter to be considered and investigated.

Some of the early fittings and methods of installation certainly would seem to justify any fears that the insurance interests may have entertained. I can remember when, back in the eighties, if the notches cut in floor timbers for gas pipes happened to be large enough, they were considered as a providentially prepared place for the wires, one on each side of the pipe. Now, through coöperation between the two parties in interest, how all this has changed; for I can stand here and tell you from the insurance interests that I believe any undue hazard from electricity has been and is being guarded against. You now give to us the safest illuminant and the safest source of power that we have. We welcome you in that you displace the open flame of gas or oil and the fire under the boiler, that you may by small power units do away with much shafting and the inherent liability of hot bearings. In order to retain this good opinion, however, we must continue our coöperation so that as your art progresses in giant strides, we may together keep pace with it in restrictions which shall not obstruct but safeguard its advance.

My great desire has been and is to foster and encourage this coöperation for our mutual benefit; our interests lie in the same direction, we must travel along together and put up with each others' faults whether we will or not. Shall we not walk as companions rather than enemies? Neither of us has a right to all the good things, nor deserves all the bad things; let us share the good things we each have and help each other with the bad things we must meet.

From the National Fire Protection Association, I bring you all a greeting and an assurance of a welcome if you will share their great work. From the underwriting interests, I also bring you greeting and assurance that we like you better as we know you better; but to the ordinary underwriter you represent a strange and unfamiliar creature, electricity, very difficult to comprehend. You do not know what electricity really is yourself, and how should we? It has served its time as a convenient substitute for our old friends, rats and matches and spontaneous combustion; it has proved its usefulness in many ways to us; it is rather erratic and sometimes inclined to stray from the path assigned to it, but on the whole it has improved so much, as it is reaching the age of maturity, that it is no longer of any particular use to us as a bugaboo to scare people with. Shall we not join hands and work together even more closely in the future than we have in the past?

## DISCUSSION ON "ELECTRICITY AS VIEWED BY THE INSURANCE ENGINEER. SHOULD THE A.I.E.E. INTEREST ITSELF IN FIRE PROTECTION?" ATLANTIC CITY, N. J., JUNE 29, 1908

**Chas. P. Steinmetz:** The matter of fire protection is of extreme importance, and the Institute should certainly actively coöperate with other organizations in the effort to reduce the risk. I believe, however, the question is a far broader one than that of fire hazard. Electrical fire hazard may be of interest to the fire underwriters, but it is equally important that the Institute should consider the danger of electric power to human life, to invested capital, to the destruction of apparatus, etc., even if the destruction does not mean an increased fire hazard. The Institute is the one body which could take up this subject in its broader aspect. I think that the Institute should appoint a committee dealing with such questions. Such a committee may better existing conditions by establishing rules. A safer and better way for the committee to act would perhaps be to obtain papers that reflect good engineering practice, calling these papers to the attention of the public at large. This would be more effective than the formulating of a lot of rules. These papers could discuss the practice of carrying extra high voltage lines through towns and cities and indicate good practice in overhead lines of different voltages, and whether these overhead lines of different voltages should be on the same poles or not. Rigid rules on all these matters cannot be insisted upon, but in a paper an author can readily state his views and thereby bring the matter before the whole Institute for discussion.

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# WATER POWER DEVELOPMENT IN THE NATIONAL FORESTS. A SUGGESTED GOVERNMENT POLICY

BY FRANK G. BAUM

In order to insure the supply of timber and to protect the water sheds and conserve the water of our mountain streams, the government some years ago adopted the policy of withdrawing large timber areas from entry by creating national forests. The forests were to be operated by the forestry department for use and not for profit. Recently the government has given permits to companies proposing to make power developments, on condition that the permits be revocable at the pleasure of the Secretary of the Agriculture, and that there be a conservation water royalty charge by the government on the power output of the plant.

Objections to temporary permits have been made by the power companies, as no one wishes to invest money at the risk of losing it through the whim of some official. Objections have also been made to the conservation charge, especially when it is based on the output of the plant. In this paper I shall try to arrive at what I believe to be a logical conclusion of a fair conservation charge.

The matter is of great importance, because power development is advancing the progress of the country at an increasing rate, and a government policy retarding power development will hinder this progress. Power development stands to-day at the same stage, so far as its influence on progress is concerned, as the construction of railroads did 20 or 40 years ago. The immense benefits to be derived from the development of cheap power and the resulting saving of our timber, oil, and coal resources should not be deferred by an unfair government policy or indefinite assurances for the safety of the money invested.

The proper development of water powers would utilize resources now going to waste; the development of coal mines, on the other hand, means the consumption of resources now stored and available at any future time. Every hydroelectric horse power saves the consumption of about twelve tons of coal per year. Therefore the proper development of the water powers would conserve the country's coal resources to that extent. For example, 1,000,000 hydroelectric horse power transmitted to New York and its vicinity for manufacturing purposes would result in saving about 12,000,000 tons of coal per year. This coal could be reserved for domestic purposes. This is about 20,000 cars of 50 tons each per month, or 666 cars per day. The development and use of less than 25 per cent. of California's available water powers would stop all wood, oil, and coal burning for power purposes, including all railroads in that state. The same is true for nearly all the western states and a great many cf the eastern and southern states.

In order to limit speculation, and at the same time to hasten water power development and save our wood, oil, and coal resources, I suggest that all rights-of-way and lands necessary for this development be given on condition that a certain proportion of the work be done each year and that a certain proportion of the development be completed within five years. This would put the man developing the water power on exactly the same basis as the miner and the farmer; it would prevent speculation and limit the operations to bona fide developments. No man or combination of men, no matter how wealthy and greedy, would then be able to monopolize the water power resources of this country. The statement that there is now danger of a water power monopoly in this country is utterly absurd to any one having a knowledge of the facts or the conditions under which water power developments must be made. The development of our water areas would help to conserve the coal areas, and would protect the national forests, where water power is developed, at no expense to the government.

It will be assumed that the object of the proposed conservation charge is not intended as a means to raise revenue for the government, but for the purpose of protecting, operating, and maintaining the forests, so that the greatest possible use may be made of them, not for this year or next, but with the idea of using the forests to produce a perpetual supply of food, timber, water, etc.

It follows as a natural consequence that the different reserve sections must stand on their own merits; that is, the revenues in California, for example, should not be made so great that it would be impossible to use the revenue in the reserves in that section. In other words, it would be only fair that the revenue derived from a California reserve, say, should not be used to purchase, or maintain, a reserve in Maine.

It follows, further, that each reserve unit should stand on its own merits, and the money derived from any one reserve should, as far as possible, be used to maintain and promote the interests of that particular reserve unit. The people entitled to the products of the reserve, who should be given first consideration, would be those who settled in the country, many of them having *settled because of the resources in the reserves* adjacent to their place of settlement. Naturally, they should be entitled to first consideration in disposing of the products of the reserve. Those who settled in a particularly favorable location should not contribute to the reserves of a less favorable condition. This policy is, I believe, followed in giving grazing permits, and also in timber permits.

Coming now to a particular reserve. The reserve has resources mainly in feed, timber and water. The area of the feed and timber product of a reserve has no natural boundary. When we consider the water product, however, we find natural boundaries for each watershed, and logically to arrive at a fair and equitable basis for a conservation water charge we must consider each water shed by its natural boundary, and each watershed as a unit. The man wishing to make a power development should pay only a just proportion of the cost of maintaining the watershed and conserving the water. In a certain reserve, for example, there are two adjacent watersheds. The area of the two watersheds may be the same, and the water output also, but the cost of maintenance of the reserve lands in one shed be entirely different from that in the other; the value of the power resources in the two adjacent watersheds may be entirely different. Watershed A for instance, may, have an area of 100,000 acres, a water output of a certain number of average second-feet, and the power which can be economically developed, say, 5000 kw. Watershed B may have the same number of acres, but the economical power development may be 50,000 kw. On the basis of a fixed charge per kilowatt-year, as proposed, watershed B would give a revenue to the government ten times as great as that of watershed A. The revenue derived by the government on this basis from watershed B from the power resource, is much more than justifiable, considering the cost of protecting and maintaining same, and much more than can possibly be used in that particular watershed for any purpose benefiting the power privilege. It is only fair that the government's charge against the power privilege should be based *on what the government furnishes* to make the privilege operative. The cost of maintenance in the case A might be very much greater than in the case B, yet the revenue derived from B, on the basis of a fixed charge per unit of output, would be ten times as great as the revenue derived from A. Some parallel examples will illustrate the principle of the proposed method of fixing the charge.

The Reclamation Service, in charging for reclaiming lands, applies to each district all the cost equally to all the lands to be irrigated. If one watershed district offers opportunities for developing a project for $20 per acre, that is the charge made, although in the adjacent watershed, or district, the charge may be $40 per acre. That is, the principle is recognized that *the people settling in a particular area are entitled to all the natural resources belonging thereto.* No profit can be made from one area and applied to another. Similarly in power development, the man who develops in one watershed is entitled to all the natural advantages belonging to that area, and he should not be made to pay to help develop power on an adjacent watershed. None of the money contributed by him, because of his privilege, can be used rightly for any other purpose, except to benefit the watershed or privilege which he enjoys. The grazing and timber interests pay their just proportion of the cost to the government of the privileges enjoyed by them, and the power privilege should likewise pay its just proportion.

Suppose again that the government withdraws a given timber area in order to assure ties to several railroads that traverse it. What is a just charge for the ties? A charge on the gross or net revenue of the road, or a rate on the tonnage passing through the reserve would be absurd; the only fair charge would be on the value of the ties, calculated on the yearly expense of maintenance and the number of ties the reserve can produce annually. Why then should the water-power company pay a royalty on the basis of its power output? The grazing and timber interests are not taxed with the idea of producing a profit to the government, or that the grazing or timber interests of one section should support those of another, or that these interests should be taxed to support others. The miner is not charged a royalty by the government, but the government can rightly charge him for any direct benefit he may receive by reason of the reserves.

By all precedent, then, the principle is well established that the government should calculate the cost of what is furnished, and the conservation charge be made accordingly. This would establish the principle that the annual conservation charge should be based on the actual yearly cost to the government of the cost of conservation. The conservation charge would change from time to time, but there would be a definite basis for its determination.

Rights-of-way on lands occupied for reservoirs, pipe-lines, and power houses should be sold to the power company at a fair value, and these lands would not then enter into the determination of the conservation charge. Rights-of-way and lands necessary for the development should be the property of the company. These matters should be fixed independently of the conservation charge. We should not expect railroads to open up new country if their rights-of-way were revocable, or if they were charged on the basis of tonnage carried over the right-of-way.

Coming now to the analysis of a particular watershed and the privilege granted to the power company on it: the withdrawal and protection of the timber will generally affect the stream-flow, and a just charge can be made by the government for the protection given, as it directly benefits the privilege. The charge made for the protection of the timber and the stream-flow must naturally vary with the conditions, and must be calculated for each case, because other interests should also pay their just charge for the protection. The charge made for the reservoir privileges, rights-of-way, for canals, pipe-lines, and power-house sites should, however, be based on the value of the acreage occupied. Because a power development occupies a given piece of ground, makes it no more valuable to the seller (the government) than if it were to be occupied by a quartz mill, and the power man should pay no more than the miner or any other interest.

When the amount to be charged for the right-of-way, reservoir, and power-house sites is fixed, and the government has determined the amount to be expended yearly on the watershed, the amount to be charged for the power privilege can be easily fixed. It should make no difference in the charge whether 5000 kw. is obtained in power, or 50,000 kw. That is, as in the case of the farmer and the Reclamation Service, the man settling in the valley where conditions are favorable for low cost of irrigation should have the benefit of that condition. And the power man who uses his ingenuity and money to discover a better power development than another should also have the benefit of his enterprise. The government has not yet, and I hope never will, put a tax upon discovery, invention, and development.

Still further to show the reasonableness of a fixed total charge annually for a given watershed, we may merely cite the fact that if the charge is based on the kilowatt output, the man who puts in a cheap and wasteful system pays less than the man who puts in a more expensive and efficient system. Further, the man who sells his power for $20 per kilowatt year, pays double the percentage paid by the man who sells for $40 per kilowatt-year. And again, the man who takes this power to a market, say 100 to 300 miles away, must pay to the government for the losses and expense in doing so and pays more than the man who sells to the home market. The man who reaches out with his power is equalizing conditions, just as railroads equalize conditions by their transportation facilities, and should be encouraged and not taxed for doing so.

Coming to the case where the government owns part of the property necessary for the conservation and development, and part is owned by private parties, or the man making the development. For example, assume that the power company making the development owns a reservoir which controls the stream. Assume that this reservoir is the controling feature of the development, that without it the stream is virtually worthless. It may even be that the reservoir is all that is necessary, and the protection of the timber could have no effect on the development, and its removal would not affect the development in the least. Has the government a right to make a conservation charge when as a matter of fact the man is paying for his own conservation? In this case the government can only charge for rights-of-way and lands occupied, and no conservation charge can be justly made. If the government furnishes part of the conservation—this is usually the case—then a proper proportion of the basic rate of the conservation charge can be made.

This may be illustrated by taking the case of a man owning a timber area to which he had title before the establishment of a reserve. In order to make use of the timber it is necessary to obtain from the government land for a mill-site and right-of-way for a railroad from the timber to the mill-site. A proper charge for the land for the mill and right-of-way can only be made on the basis of the value of the lands occupied. A charge on the output of the mill would be entirely unjust; this will be admitted by all. Change the timber area to a reservoir, the mill-site to a power-house site, and the railroad to a pipe-line, and wherein lies the difference? The man purchased the reservoir before the reserve was established, to store water and develop power. In order to do this he must have the right-of-way for pipe-line and land for power-house site, and these must be granted him as in the case of the sawmill, on the basis of the land value, and not on a royalty of the power output. No royalty should be charged for giving the man the only opportunity there is to make use of his property. Any number of parallel cases could be cited to illustrate the principle. In creating a forest reserve the government cannot but recognize the rights of private individuals or companies who owned lands in the reserve previous to its establishment, and the government must allow owners the use of their property. Any other course would amount to confiscation.

The above suggested method of fixing the conservation charge is believed to be logical and treats the power interests as others. The amount to be charged yearly for conservation would be influenced by only one fact; that is, the yearly cost to the government of maintaining the area benefiting the privilege, and what proportion of the charge should be borne by the power company? It eliminates all questions as to the efficiency of the development or the amount of development, and *hence would tend to make for efficiency and maximum use of the resources.* It eliminates the question of the market value or distance of transmission. The market value would, as it should, depend upon the natural advantages for power development in the district, and there should be no additional tax when high efficiency is aimed at or long transmission is undertaken.

Rights-of-way and property necessary would be a separate matter from the conservation charge, and property rights necessary for development would be not temporary but permanent. We should not expect a man to establish his permanent home and develop his farm if he is not assured title.

The above method of charging separately for lands and for conservation, and giving title to lands, would remove all objection on the part of investors, because then power companies would obtain title to grounds occupied by the development and there would be a definite and fair method by which the conservation charge would be arrived at, now or at any future time. It is believed no logical objection could be raised to the plan by the power companies.

It may be contended by some that the government should obtain as large a revenue as possible for every development and apply the proceeds for the general welfare, the argument being based on the fact that the government grants a privilege which cannot be enjoyed by others and should receive a revenue in proportion to that derived from the operation of the privilege. The examples cited, however, make this position untenable, as the power companies should not be treated differently from the farmer, the miner, the lumber company, the railroads, or other interests. There is no monopoly in water power development, and the advantage gained by a man who does something should not be shared by the man not so progressive. It would be just as logical to make the thrifty farmer share with the less thrifty. Industry, progressiveness, and individuality should not be stifled or taxed.

Feed, timber, all crops, minerals, water and water products, and anything which nature produces, are primary producers of wealth. Why should water be classed differently from any of the other natural products in the government policy of development and control? *The general government cannot justly make a charge equivalent to a franchise tax or regulate rates; those privileges would remain with the state and subject to local laws, where the streams are under state control.* My understanding of the law is that all streams, except those that are navigable, are under state control.

When the conditions of the past, present, and future developments of the country and its industries are considered in relation to the present and future developments of power, it is believed that the only tenable conclusion which can be reached is that the power interests must be treated as other interests and *charged for conservation only on the basis of the cost to the government of the thing furnished by the government*, and that rights-of-way and property required for the development should be the property of the company making the development. The only varying element, then, will be that due to the fact that the value of the property owned by the government is changing as time advances, and the conservation charge should be changed accordingly.

The conclusions drawn from the above discussion may be briefly stated as follows:

1. Rights-of-way and lands necessary for the development should be charged for on a fair basis of value, as would be determined if the lands belonged to private parties and a value had to be set on them for the power purposes by a court, or a commission. Rights-of-way and lands necessary should be deeded outright by the government to the power company and the only changing conditions then, as time goes on, would be the yearly conservation charge.

2. A proper conservation charge can be made only on the basis of the cost to the government of that which is furnished by the government.

3. The right to charge a privilege or franchise tax should remain with the state and subject to local laws as conditions warrant.

A. The conservation charge will have a maximum limit at any given time which can be determined by calculating the yearly cost of the conservation to the government. This charge can be fixed for a period of say ten years, and at the end of that time a re-calculation may be made, and a new conservation charge made yearly, to meet the changing cost of maintenance.

B. The proceeds from any particular privilege should not be devoted to any other watershed or any other section, or for any purpose except the particular privilege.

C. The question of the proper conservation charge is entirely a separate matter from the charge to be made for lands and rights-of-way for development, and the two matters should be kept distinct.

My suggestion for a government policy on water-power resources can finally be stated in a single sentence—encourage water-power development as much as possible, make a proper conservation charge, based on the cost to the government, and make grants for rights-of-way and lands necessary for development permanent on condition that a certain proportion of the work be done each year, and that a certain proportion of the development be completed within five years when a patent for all grounds occupied will be granted, reserving to the states the right to charge a privilege or franchise tax as the conditions warrant.

## DISCUSSION ON "WATER POWER DEVELOPMENT IN THE NATIONAL FORESTS. A SUGGESTED GOVERNMENT POLICY."

### ATLANTIC CITY, N. J., JUNE 29, 1908

**J. H. Finney:** Mr. Baum's paper is an interesting presentation of his views as a "power enthusiast and a believer in a cheap source of power," and his belief that "cheap power is vital and necessary to the present and future development of the country" will be, I am sure, supported heartily in this assemblage. We may also be classed as power enthusiasts. I think, however, that his presentation of the case is wrong from several standpoints:

1. In considering the national forests, wherever located, in the light of a local asset and not as a national asset, in which all the people should share.
2. In basing a power charge or franchise solely on the cost of forest conservation and not on the value of the grant fixed by the earning capacity.
3. In the attitude which assumes that a policy other than that outlined by him would put a tax on discovery, invention, and development, by ascribing to capital and genius, seeking legitimate investment and fair returns, attributes that indicate a selfishness fortunately not always true.
4. By a disregard of what might be termed the "rights of the people" in and to an asset of perpetual value, national and not local in character, a value that increases from decade to decade, as coal becomes scarcer and dearer.

Let us first see what the government's stand is on the question of charges. It can best be stated in a general way by quoting President Roosevelt's specific statement before the recent Conference in Washington.

> My position has been simply that where a privilege, which may be of untold value in the future to the private individual granted it, is asked from the federal government, that the federal government shall put on the grant a condition that it shall not be a grant in perpetuity. Make it long enough so that the corporation shall have an ample material reward. The corporation deserves it. Give an ample reward to the captain of industry, but not an indeterminate reward. Put in a provision that will enable our children at the end of a certain specified period to say what in their judgment should be done with that great natural power, which is of use to the grantee only because the people as a whole allow him to use it. It is eminently right that he should be allowed to make ample profit from his development of it, but make him pay something for the privilege and make the grant for a fixed period, so that when the conditions change, as in all probability they will change, our children, the nation of the future, shall have the right to determine the conditions upon which the privilege shall then be enjoyed.
>
> Where that policy can best be carried out by the state, carry it out by the state; where it can be best carried out by the nation, carry it out by the nation. My concern is not with the academic side of the question; my concern is in the employment either of the principle of states rights, or the principle of national sovereignty, as will best conserve the needs of the people as a whole.

This is a clear statement of a just and righteous intent, and who among us will question its honesty, or the wisdom and desirability of its proper and successful accomplishment? This policy has, I believe, been more specifically elaborated by the Forest Service in certain cases, involving governmental grants as a definite policy, namely:

(*a*). The charge for power permits should be based on the power value of the land occupied and the value of the services rendered by the government.

(*b*). The proceeds from any particular permit may legally be appropriated by the Congress for any public purpose, and, under the same policy, may properly be used for the expense of administering in national forests, or for the reclamation fund, or for the proposed inland waterways fund.

(*c*). The plan of calculating the maximum conservation charge upon the yearly cost of forest conservation to the government would be impracticable, for the additional reason that such cost ought to be vastly higher than it is now. In the European forests the cost is several dollars per acre, as against one cent per acre this year in this country.

(*d*). The question of the charge for power plants is a unit. In considering it, the rental value of the land and the value of the services rendered by the government in forest conservation should and must be considered together.

(*e*). The rental value for power purposes of the lands occupied should be paid by the permittee, not merely their value for forest purposes, farm purposes, and the like. The government is entitled to their value for all purposes, especially including the purpose for which they are actually occupied. This value must be fixed by the administrative officers of the government at such a rate as will encourage the taking of permits. But the government should retain permanent ownership, subject to the temporary right of the permittee to use the land.

(*f*). Practical considerations of administration make it desirable that the charge for power plants should be uniform. It has therefore been fixed at a rate which is believed to be sufficiently low not to check the development of any project.

While this policy may not be yet fully worked out, perhaps may not be the final word, it is, I maintain, in exact accord with the views and policy which the President seeks to establish, which in its final analysis is simply equal justice to both grantee and grantor, in rights which involve the use of the common property of the people as a whole, rights which are in their strictest sense, ours only as trustees and guardians for the future.

It may not be amiss to say here that this idea of trusteeship, while not strictly new, has in the past few years attained a new significance; and there are evidences of an awakening of the public conscience in respect to our guardianship and to our obvious duty to ourselves and to posterity in these matters that betokens a better America. The whole conservation movement, crystallized by the notable conference just held at Washington, marks, I believe, a new era in American thought and American habit.

*Forests as a national asset.* The national forest in the West is the heritage of the whole people. No state or local boundaries were in the mind of the Almighty when the forests were first planted by him. No state boundary now confines their use or benefits or value to the state alone. The California forests serve other states in water conservation, in water power, in climatic effects, in supplying timber, grazing, etc., and the same is true of forests whether located in Wyoming or Washington or Idaho. They are public domain, belonging to the nation, not to the states containing them. They are, therefore, in all the benefits and profits accruing from them, the common property of the nation. The state fortunately containing them gains the greatest benefit, and rightly so, but no claim that they are the exclusive property of the state as regards benefits or profits is tenable. The nation is the sovereign, and as a matter of fact and right the profits from them, while in part shared with the state, are converted into the national treasury. They should be turned into a forest fund that could be used to establish other national forests.

In the east where the Appalachian national forest is projected, and so badly needed, the situation is different only in degree. The states agree to relinquish sovereignty, the title passing by purchase to the new owner, the federal government. The states will get their share of profit—the balance goes into the treasury. Nor can the forest here be considered a local asset. The states are manifestly unable to act effectively in its establishment. The very fact that the national government must act shows its interstate, its national character.

From the forested mountains of North Carolina flow streams that make power and navigation possible in streams in adjacent states—north, south, east and west. Some twenty states are directly, and the whole nation indirectly affected by what North Carolina does, should she denude or preserve her forests. It cannot be considered, therefore, as a local question, and I think Mr. Baum's view is narrow and untenable. Does the San Francisco post office expend its surplus only on San Francisco's postal service, or the New York post office on New York's? Is not the profit from these larger and more prosperous centers used to improve the efficiency and value of the postal service as a whole to the whole people?

Let us look into this a moment. The government at present sells the timber on the basis of its selling value, because the timber costs have been to the present time practically nothing, except the small value of the land set aside, and the maintenance and patroling and similar charges. We have not begun to spend on our forests the amount of money which they should have yearly for a definite reforestation policy. Will Mr. Baum advocate this charge against the power company, should we spend, as we some day must, large sums for reforestation?

The national forest, so far as the timber is concerned, was operated at a loss last year. Other forest products considered, there was a substantial profit, and this profit is increasing year by year, and rightly so. Forests become without impropriety a profitable investment to the government, without imposing any purposely designed hardship on the grazer or lumberman or miner or homesteader. If the government has instead of grazing privileges, or lumber, a water power to dispose of, in what respect does it differ from the other forest products? Is not its value what it is worth to the grantee, whether it be five thousand or fifty thousand kilowatts, and is not this value fixed solely by what it may be able to earn as a return on the investment? The 5000-kw. plant may be just as able to earn a fair return as the 50,000-kw. plant. The promoter or the developer might prefer the larger plant, perhaps, as offering more chance for profit, just as a street railway in New York might be a more attractive enterprise than one in Atlantic City, and yet both New York and Atlantic City have street railways, and it is barely possible that the smaller one is the more attractive investment.

It is largely a commercial problem. The 50,000-kw. plant would not be developed if no profitable market existed, even if there were no charges imposed by the government. Commercial considerations govern. There are plants operating and making money where fixed charges are abnormally high, costing $200 or so per kilowatt installed, and selling power at a low price, too; there are others that have cost $80 or less per kilowatt installed that are selling power at a higher rate than the other plant. They all fix what is claimed to be a reasonable charge for current, under the conditions existing in their particular field, and this charge varies quite as much and as radically as the installation costs. It is a reasonable charge at one cent per kilowatt-hour, or two or more, depending on local conditions. We cannot well object to a metered tax on production when we are at the same time through our public service companies, such as the power company, the telephone company, the gas company, and the water company, strenuously and persistently advocating a metered charge for consumption. It is not possible to impose an equitable tax in any other way.

The plant that has so narrow a margin between success and failure as to be seriously affected by the imposition of a fair tax, whether this tax be 1/1000 cent, or 1/100 cent per kilowatt-hour, or even more, perhaps, has small prospect of attracting investors. It is not at all impossible or difficult—we are doing it every day—to get at exact figures of development costs in any project contemplated, and accurately to estimate its earning capacity. We are doing the latter, too, every day. One needs only to recall the engineering reports of the past and the present to see that it is done on the basis of "what the traffic will stand," nor is there impropriety involved in this. When this is done and the property cannot stand a reasonable tax on its output, that project is not a commercial one at the present time and under present conditions, and must await development, as does many another, until a more favorable season.

*A tax on discovery and invention.* There are no inherited or inherent rights in capital privately to exploit our remaining resources in mines and lands and forests, although this statement seems unduly optimistic in the light of past history. The Americans are over-patient and have been over-exploited, to put it mildly. There may be no power monopoly contemplated, though a water power company is by nature a monopoly *per se.* It is many times the only possible source of supply of a given market. The opportunity for monopoly unquestionably exists in many places now, and there are some striking examples of what might happen to water power in what has happened in the past in some notable combinations of certain railway and other large interests that can be readily recalled.

The government imposes a tax to-day on inventive genius by charging for a patent—the child of one's brain—a uniform charge regardless of the cost of maintenance of a patent office. It fixes also a limitation of the grant to seventeen years—but the Patent Office is full.

No fears are justified, however, that the imposition of a tax, which would net him forty-nine per cent. instead of fifty per cent., or five and nine-tenths instead of six per cent. on a solid investment, will curb either the American's ingenuity or his inventive genius, or his discovery of the quickest way to get the forty-nine per cent. or five and nine-tenths per cent., if he cannot have the larger returns.

*Disregard of the people's rights.* The real ownership of these natural assets in mines and forests and soil and water clearly lies in the people as a whole—a part of the nation's heritage, whether natural or artificially created through governmental agencies. Some profit therefrom belongs to the people, just as clearly and on the same broad ground as that some profit belongs to the capital and brains developing them. With this right of the people to profit, there exists and there is imposed the duty to fix reasonable restrictions on their use. Rights to exploit them properly should be granted on the basis of a definite term of years for the franchise; a definite basis of fair charge on the output; fair regulation by the government—a policy that is embraced in what is termed "a square deal" to all concerned; to the investor, to the corporation, to the power user and to the nation, and, incidentally, to posterity.

As engineers, knowing better, perhaps, than any other class of observers the immense potential value represented by forty trillion cubic feet flowing annually within our borders, descending an average of twenty-five hundred feet to the sea, and what it means to present America and its future value to future America; dimly realizing the infinitely greater value and incalculable good of our waters in the light of the new concept of them in their substance, or corpus, we cannot go on record as indorsing any plan involving their exploitation and use, that does not have strictly in mind, not only their fullest development and conservation in the largest sense for power, for soil, for water supply, for the health and very life of the people, but the plan must be one that will do equal justice to all and contain special privileges to none.

No less an authority than Jefferson declared that " the earth belongs in usufruct to the generation at any time living upon it." This view is as true to-day and as free from demagogy or socialism as when uttered. It is plain common sense and common honesty, and we as a people are at last beginning to realize it.

**E. R. Taylor:** I would like to see Mr. Baum's paper broadened out, and my criticism is mostly upon paragraph B, in which Mr. Baum says:

> The proceeds from any particular privilege cannot be devoted to any other watershed or any other section, or for any purpose except the particular privilege.

I had the honor to read a paper on " Forestry, Water Storage, Power and Navigation " before the American Electrochemical Society a few weeks ago. In that paper I think I advocated the converse of that advocated by Mr. Baum in paragraph B. I said there:

> Let each state or section develop one or two streams completely with forest and lakes (and even farmers' tributary brooks to be paid back at cost) as illustrations, and put them to work earning money to develop others later. Let coöperation be the watchword. Private interests cannot do it as it ought to be done; public interests must do it, and the doing will be immensely profitable and a benefit for all coming time.

All of us realize the great value of these water power privileges, if they are rightly developed, and I suggest that all who are interested in the subject get a copy of the Third Annual Report of the New York State Water Supply Commission, which deals with this subject.

**P. P. Wells:** I desire to explain briefly the forest service policy with regard to what used to be called the conservation charge. I am not a trained engineer and must ask your indulgence on that side of the question. The service is very much indebted to Mr. Baum for the careful consideration he has given this subject. However, we agree with the conclusions that have been expressed by Mr. Finney.

Mr. Baum's paper does not clearly distinguish between the policy of Congress and the policy of the Service—the Administration. Of course, to find out about the policy of Congress we seek the statutes. In respect to the policy of the Forest Service as an administrative body I wish to say something about what its intentions are, what it has done, and what it would like to do.

In the first place, it does not like the present system of having permits for water power development revocable at the discretion of the secretary. That condition is imposed by the Act of Congress of February 15, 1901, in which it is expressly provided that they shall be revocable. The Forest Service would like to have authority to issue permits which would be irrevocable except for breach of conditions, for terms sufficiently long to guarantee security to the investor and a chance for full development.

At Mr. Pinchot's suggestion there was included in the Agricultural Appropriation Bill pending before the last session of Congress, a clause which would have given power to issue irrevocable permits for a term of fifty years. That clause, like all new legislation in appropriation bills, was subject to be stricken out upon a point of order raised by any one member of the House of Representatives. Two members made the point of order against this clause, and it was consequently stricken out.

As the law now stands, the service has gone as far as it can to give permanence. It cannot take away from the successor of the present Secretary of Agriculture the power to revoke the permit. It does, however, specify precisely, before construction begins, the maximum charge that is to be made in every case. This is fixed in every permit for a term of forty years, so that the service has gone as far as it possibly can to give certainty.

Secondly, for the reasons explained so well by Mr. Finney, the service stands for the permanent government control of its great natural resources, and as each fifty-year license expires, new conditions may be then imposed in accordance with the changed circumstances that face the men of that time.

Thirdly, the policy of the service is that no permit which is issued shall be held unused. Pressure is put upon the permittee to make full use of his permit, first, by making a preliminary small acreage or mileage charge pending construction; secondly, by fixing in the permit a specific time in which construction must begin and another specific time in which it must be completed. That time will be extended at the discretion of the Forester, if unforeseen physical obstacles are met with.

Fourthly, the service stands for a uniform small charge or annual rental based on the amount of power developed. The justification of this charge, as Mr. Finney has explained, is that the title of the government to lands in the national forest is unquestioned and absolute. They belong to all the people of the nation. Whatever value there is in them belongs to all. If you consider this value, there are three elements in it, bearing on this matter, which we may call the land resources and the services rendered by the government. In these cases, with respect to water power, the "resources" of the forests may be taken to be the water alone, considered apart from the land itself. Our charge is not based on this element at all. The appropriation of water is made under the state laws. The second element is the value of the land as a power site. It is obvious that one piece of land may be very valuable for that purpose, and another piece of land less valuable, because either of advantageous reservoir sites for storage purposes, or because of a greater fall or head. The third element of value is the service of the government in maintaining a steady water flow by forest conservation. This last is the only element that Mr. Baum's paper considers.

In my opinion, Mr. Baum's analogies do not bear out his arguments. In the first place, it has been for many years the policy of the government to give free homes to settlers, and in furtherance of that policy the government irrigates arid lands at cost for homestead settlers. The present administration does not believe that that policy should be extended to large corporations, who use the public resources primarily for gain. So there is a broad distinction between the homesteader and the commercial user of natural resources that belong to the government.

Take the case of the mineral fuels. Two years ago the present administration definitely announced its policy as that of a lease system, rather than the present system of alienation of coal and oil lands in perpetuity. Take the case of railroad grants and free rights-of-way for railroads; that policy was initiated when the resources of the country were thought to be inexhaustible, and when the Pacific coast had to be connected with the East for political reasons. But the reasons for that policy no longer exist and they do not apply in the matter of water power. Take the case of timber. Timber is required by law, under Act of June 4, 1897, to be sold at public auction to the highest bidder, without regard to the cost of administering the particular forest on which it is sold. Railroad ties, which Mr. Baum's paper mentions, could only be sold in this manner, without any reference whatever to the cost of forest conservation. Grazing fees on the forests are an attempt to approximate the grazing value of the land. So with mill sites; if a man wants a saw-mill site, as Mr. Baum mentions, we vary the charge precisely in accordance to the capacity of the mill. Thus all the analogies, except that of the homesteader, are against the position taken by Mr. Baum.

A word as to what Mr. Baum says about deductions from the charge on account of private ownership of land. It is a settled part of the policy of the Forest Service, that if a power plant occupies unreserved public land, over which the Forest Service has no jurisdiction (private land), a deduction will be made on that account, provided the patent by which the private land was acquired did not reserve to the United States a right-of-way for canals, etc., constructed under the authority of the United States. All patents for lands west of the one hundredth meridian, issued since the Act of 1890, do make such reservations.

Then as to water storage; the policy of the service is to encourage the conservation of water by storage, done by permittees, in such manner that they will not be charged for the conservation of the water they store. They will, however, be charged for the head which they get from the use of the forest lands, which makes this stored water valuable to them; in other words, there is a fifty per cent. reduction from the maximum charge on account of power produced by stored water which would not be produced by the natural flow.

In respect to what Mr. Baum says concerning the reward which should go to the enterprising discoverer of the best power sites, a uniform charge is made, believed to be low enough not to obstruct development on any practicable site. It therefore leaves a wide margin of profit for the enterprising discoverer of a better site, and that margin is the wider as the site is the better.

**A. H. Babcock:** Paragraph B of Mr. Baum's paper has caused considerable discussion. It is my opinion that Mr. Baum had in mind the fact that in the case of a water power development, the power must be utilized within a limited area. The consumers in the area must pay the government charge; hence they are entitled to the benefit. The charge should be made as low as consistent with the development of that district. Mr. Finney's analogy to the post office charges being distributed for the benefit of the whole country does not seem to me to be a happy one, for the reason that a two-cent stamp must carry the service into rural districts and other places, where an adequate delivery system otherwise could not possibly be maintained.

**President Stott:** Some very important points have been raised in the paper and discussions, which I would hear brought out at greater length.

**C. P. Steinmetz:** I hardly need to say that I thoroughly agree with the opinion, that the preservation of our national resources is a most important problem requiring energetic and prompt action. I am sorry to say, however, that with regard to the methods proposed by Mr. Baum I must disagree in almost every particular. The first argument made by him is that the different water power developments should stand on their own merits; that is, that the proceeds from any particular privilege cannot be devoted to any other watershed, or any other section, or for any other purpose except the particular privilege. He contends that the development of the watershed should be considered as a private matter in that particular locality.

I do not agree with that suggestion, as I believe that, if followed out, it would defeat the very thing we are trying to bring about. It is the same argument which can be made, and is being made, against setting aside and preserving these national resources, that they are not of general, but only of local interest. It is of no benefit, it is claimed, to the Central States, to set aside the Appalachian reserve, or the White Mountain reserve, and therefore the Central States say they do not want the national government, to which they contribute, to pay for doing it.

That is Mr. Baum's argument, but I believe his argument is wrong, and there is a contradiction in the very statement, which Mr. Baum has overlooked. He starts his paper by speaking of the preservation of the *national* resources, and then he says that these resources are only of *local* interest, and should be developed and paid for locally. If they are of local interest only, then they do not need the aid of the national government, but should be left to local enterprise. Under such circumstances I should prefer to leave them to private enterprise. The only reason for calling on the national government is that the subject is not of mere *local* interest, but of *national* importance.

It may appear at first sight immaterial to California whether the water powers of Maine are developed or not, but if the failure to develop the water powers in Maine results in an increased consumption, say, of one hundred million tons of coal, the coal famine resulting will increase the cost of pig iron or structural steel to California as well as to Maine, and so one part of the country will suffer by the destruction of our national resources, by the waste of our national capital, equally with every other part. Hence it is not a *local*, but a *national* problem.

If the problem were merely to develop water powers, then indeed it would be local; but the problem is much broader, it is the problem of preserving and protecting our national capital. Suppose for the sake of argument the cost of the development of the water power is charged to the individual location. Then there would be developed only those watersheds where the cost is lowest and the power greatest; that is to say, those cases where government aid is not needed, as private capital would sooner or later do the developing. But then the far more important problem would remain untouched; the problem where the watershed requires to be protected and would not be protected by private capital, because there is not enough power available in it to justify such protection. The destruction of timber and the erosion of hillsides at every rainfall would very soon be disastrous to the entire country. No effective protection or development can take place when this matter is considered as purely local. Such a policy would be very inefficient in carrying out our purpose of protecting and preserving the national resources, and would indeed be the surest way of defeating this purpose. As long as it is a national problem, the nation stands or falls as a whole, is responsible as a whole, and has to take care of it or benefit by it as a whole.

Whether the payment for the work is made by the United States treasury, or by assessment on the beneficiaries of the development of the national resources, whichever it may be, remains for discussion, but certainly we cannot consider the development as a matter only of local importance.

Furthermore, it would be just as unfair to charge a high power cost to a moderate water power which may be very valuable and necessary, merely because the development of its watershed was rather expensive, while another water power may be developed almost free of charge where the watershed required very little attention. A part of the argument of the paper is that the proposed method of charge by the kilowatt output is unfair. Granting that, it should not be concluded that any other method proposed by the writer is therefore the proper method. If one proposed method is unfair, it does not prove the correctness of one other method; it merely means that we should find a fairer method than that which is proposed.

I agree with the writer that a fixed charge per kilowatt may not be fair. One thousand kilowatts of power developed near New York City is vastly more valuable than 5,000 kw. of power developed five hundred miles from nowhere. You may say we make the charge so low that every one needing the power can afford to pay the charge. That is unjust again, because we then fail to make a reasonable and fair charge on the profitable water power near New York City, and therefore fail to derive as much revenue for use in developing resources as the development of water power can stand.

The last point I desire to discuss is the feasibility of Mr. Baum's proposition, that the franchise privileges must be perpetual. He claims there is no franchise or privilege, but that the matter is the same as if I buy a piece of land and build a private residence. In the same manner those which develop the water power should buy the land. He does not believe in this argument himself, however, because in other parts of the paper he uses the term "privilege" and so signifies that there is a little more involved than buying a plot of land for a private residence. However, whether we think it desirable or not, we must realize that there is a very strong and growing sentiment against perpetual franchises, against giving away national property in perpetuity, or even for a long term of years, such as ninety-nine years or fifty years. Whether this is desirable or not, we must realize that the sentiment is growing and will not reverse, and will have to be dealt with as a fact, whether we like it or not, so that it will be increasingly more difficult to get perpetual franchises or privileges, or even long-term franchises. Whatever arrangements we so recommend, we will have to count on this condition—the lifetime of a franchise will be the lifetime of a generation, or something like twenty-five or thirty years at the most.

There are thus two features which we must keep in mind; to develop and protect as quickly and as completely as possible our national resources in forests and streams and mines, and to make the development such as to induce private capital to enter into it. The problem which we have to solve is how to combine the short-term franchise with such conditions, so that private capital will invest in these water powers.

Now to induce private capital to enter this field requires that capital must be guaranteed against confiscation, direct or indirect; that is, there must be a guarantee that at the termination of whatever franchise there is, there shall be no confiscation, that the value of the plant shall be preserved as a tangible asset of the investor. As soon as we guarantee that, I do not see that it matters very much whether the franchise is perpetual or whether it is relatively short, the only just objection against a short-term franchise is that the investor has to face the condition that he must get his full capital returned with interest within seventeen or twenty-five years, because he has no guarantee or protection of the investment beyond that time. The value of the investment must be guaranteed in any limited franchise.

There is however a franchise or monopoly very much stronger than any other franchise ever dreamed of by anybody, whether a water power franchise, or a city railway franchise, or anything else. The strongest indeed of all privileges, franchises, or monopolies is the manufacture of a patented invention. There is no restriction; you may develop the invention or not, you can give the public the benefit or not. You can throw it away, and no one has any right to object. You can charge ten thousand per cent. profit if you choose, but after a limited time, seventeen years, this monopoly expires. But there is no confiscation. Whatever factories, whatever plants you have erected to carry out this invention, they are still your property, except that now this invested capital has to compete on even terms with all other industries; that is, it is entitled to a fair rate of interest, but no more fancy profits. So I believe some similar method could be developed for the similar problem of creating values, where values did not exist before, in the water powers, forests, and mines, and *unlimited* franchises for a limited time; that is, unlimited regarding restrictions, price, time of development, etc., might and should be given, because it is necessary to have the possibility of unlimited profit to compensate for the chances, which are not small, of complete loss in the failure of the power development. But that should be for a limited time only, say the same seventeen years the letters patent has to run, and after that time the franchise expires, and either the government can take over the plant at its actual value, or renew the franchise with such restrictions, limitations, or conditions, as may seem to it desirable, provided these conditions do not constitute a confiscation of invested capital.

I think this would take away the reasonable objections to the short-term franchise, and would make it feasible, by holding out chances of very large returns during the unlimited period, to take the risk of complete loss. After all, this idea of the water powers being very valuable is a misconception, derived from looking at those powers which have been a commercial success, and forgetting to look at those many other franchises, city railways, etc., which have been developed and capital sunk into them without return.

The development of a water power is just like the exploitation of a letters patent, in the fact that the success of the two is a matter of some doubt—they are properties of questionable value. The water power may be, when fully developed, of extreme value, or it may be an entire loss. It is not an unquestionable asset, like United States bonds. If you desire to get the water powers developed, and desire to interest private capital therein, you thus cannot expect to limit the returns to the moderate values of the usual conservative commercial enterprises, because you cannot limit the chances of failure, and where there is a chance of loss you must compensate for it by the chance of more than normal gain or profit.

**Wm. McClellan:** I think we all agree that the word "national" strikes the keynote of this whole discussion. Those who realize the importance of this badly misunderstood question, and have taken the trouble to investigate the conditions, have found opinion is very likely to vary according to locality. In various parts of the West and South, great water powers exist more or less in their natural state. Whatever deficiencies or irregularities they have are natural. When we come to the East, however, we find a large number of valuable water powers which may be called "spoiled water powers." This has occurred on account of the denudation of forests at the head waters. During this last winter I have had occasion to examine a number of these eastern water powers, many of them of comparatively low head. It is surprising to find how many places there are where not more than 500 h.p. can be developed at present, and yet records show that years ago, before natural conditions had been changed, there would have been at times as much as 5000 to 6000 h.p. Steps are being taken by several state commissions to determine plans and the cost for overcoming these deficiencies by making the flow of the river as uniform as possible throughout the year.

These great natural water powers of the West, needing in many cases comparatively little assistance, and the great spoiled water powers of the East, needing in some cases a large amount of assistance, all make up the heritage of the nation. The fallacy is very subtle, nevertheless it is an absolute fallacy, that these resources should be developed for the benefit of the immediate community or state. In the opinion of the speaker, these resources should be considered as a whole, and charges for development and assistance should be made in every case from the standpoint of general utility. The government, like an individual, should so manage its resources that all are brought up to as efficient a condition, with as great earning capacity as possible.

It is for engineers to say whether a good water power is a real asset of the government, and is worth developing. They are best fitted to examine the local conditions in each case, and see what change is advisable for a water power.

It is safe to say also that if this matter is not taken up on a national basis, there will be difficulties later, inasmuch as a large part of the water power of the country exists at present in locations which come under the national government, and in many other cases, where strictly speaking it is a state matter, attempts will be made to transmit power between the states. This will probably become a matter for national control some time later.

**C. H. Porter** (by letter): It seems to me that every one who considers this question must agree with Mr. Baum that the regulations of the government with reference to the granting of power permits in national forests should be such as to encourage the development of water powers and that the present regulations are unsatisfactory. That the Forest Service recognizes this is shown by the following extract from a letter signed by Mr. Pinchot, and dated May 5, 1908:

> I wish to say now that I have never advocated revocable permits. The Act of February 15, 1901, expressly requires that all permits shall be revocable. I have consistently advocated legislation to authorize the issue of permits irrevocable for a fixed term, which should be sufficiently long to give reasonable security to investors—say fifty years. During this term the permittee, so long as he fulfils the conditions expressed in his permit, should be as independent as the holder of any other property. Moreover, the conditions of the permit should define with as great accuracy as possible the maximum burden placed upon him. He would then be in a position to solicit investment in his enterprise by offering certainty and security to the investor.
>
> For these reasons I secured the insertion by the House Committee on Agriculture in the agricultural appropriation bill, now pending, of a clause authorizing the issue of irrevocable permits for fifty years. This clause was stricken out in the House. I believe that it would have been enacted into law if it had received the support of the friends of the power companies and that the companies have themselves only to blame if they are now suffering from the fact that permits are revocable.
>
> A conference between representatives of the government and representatives of the power companies and of banking houses interested in financing power projects was held in Washington in February and March. The government opened the conference by proposing legislation of the character above indicated. The companies were unwilling to accept that unless they also got much more. The administration cannot therefore be held responsible for the fact that this legislation has not been secured.

The real question under discussion, then, is whether the government should grant very valuable privileges to the power companies upon conditions more favorable to the latter than are necessary to insure the development of water powers. The power companies are justly entitled to a rate of interest on their investment proportional to the initiative required and risk involved and one which will make the proposition attractive to capital, but why are they entitled to anything more?

It is stated in the paper that the reserves or national forests were created primarily for use and not for profit, but if there be profit involved in the administration of the reserves why should it not go to the government, representing the public rather than be handed over to a few corporations? The fact that the government has in the past practically given away for private exploitation by far the greater part of the natural resources of this country is not, it seems to me, an argument for giving away the small remnant the legal title to which still remains with the government.

If the granting of permits for 50 years, irrevocable except for breach of conditions, will result in the development of water powers with its many obvious concomitant benefits, what is to be gained by the granting of permits in perpetuity, except the enrichment of a few individuals? If there is any question as to whether 50 years is a sufficiently long period to induce the desired result, it would seem to be a reasonable method of ascertaining the facts for the government to offer to grant permits for this length of time and then, if permits are not applied for, the granting of permits for a longer period can be authorized. In any case the government should retain permanent control of all water power resources now in its hands, and issue permits for development under conditions fixed for a definite period, at the end of which time the government should be free to make new stipulations and adjust the conditions to the circumstances then existing.

Mr. Baum raises the question of monopoly, and while a monopoly of the water resources of this entire country may, as he says, be absurd, a monopoly of the water powers of a given locality is certainly possible and in many cases probable. Even where there is not a monopoly of the sources of power there may be a monopoly, through exclusive franchises or otherwise, of the power market practically available in a given district. Whatever the cause, the resident of a city in California confronted with a local power monopoly will derive no advantage from the fact that Niagara power, for example, is controlled by entirely independent financial interests.

In the paper it is stated that the profits of a national forest in California should not be used to maintain a reserve in Maine, but the proceeds from the sale of the public land included in the national forest would, if the reserve had not been created, have been turned into the national treasury, and not turned over to the state of California. Why should not the same course be followed with any profits which may arise from the administration of the reserve? Both before and after the creation of the reserve the land belonged and belongs to the nation.

It is true that settlers in the vicinity of a reserve should be given first consideration in the disposition of the products of the reserve, but, in general, water powers are not developed on a coöperative basis by the people who use the power, but by bondholders and stockholders at a distance. The price of power will always be determined by the cost of competitive power, or by the price at which, with the corresponding amount of business, the profits will be a maximum, not by the actual cost to the company of the power sold the consumer. The amount of the government charge affects the last item only, but the two determining factors are entirely independent of it.

Furthermore, while it is the policy of the government that settlers in the neighborhood of any one forest be preferred to people at a distance, so far as the right to use the land and resources of the forest is concerned, it is also its policy that,

> They should pay a fair price for all exclusive commercial privileges which they get. In other words, they should not be preferred to others as to price but should be preferred to others at the same price. This is the rule in the case of grazing permits, which are further restricted to prevent monopoly by large owners.

Whether it is "only fair that the government charge against the power privileges should be based on what the government furnishes", depends upon whether the cost or the value of what the government furnishes is meant. As an analogy the case of railroad ties is mentioned, and it is claimed that the value of these should be calculated on the yearly expense of maintenance and the number of ties the reserve can produce annually. As I understand the meaning of the word "value" it is the amount of money for which a thing can be sold. As a matter of fact, in disposing of any of the timber products of a reserve, it is the market value, determined by sale at public auction after advertisement, not the cost of maintaining the reserve, which fixes the price at which the timber is sold. An exception is made in the case of the small homesteader in the immediate vicinity of the reserve, who is given free certain forest privileges for personal and non-commercial use. Thus he can have without charge a small amount of timber, $20.00 stumpage annually, and is allowed to graze free six milk or work animals. When the timber is sold to a railroad or lumber company, the government receives the market price of that kind and grade of lumber. It would, it seems to me, be absurd for the government, representing the public, to sell timber from national forests to lumber companies for a nominal sum in order that the lumber companies might make an excessive profit in reselling it to the public.

While the charges of the government to the power companies should not be excessive and should not exceed a definite maximum set in advance, in order that the fixed charges on a development may be accurately foreseen, nevertheless I see no reason why the value of the power privilege rather than the cost of maintaining a given reserve should not be taken account of in determining the government charges, just as the market value of the timber is considered in fixing its price.

The value of the land for power purposes is approximately measured by the amount of power actually developed each year. It is also an inverse function of the cost of development per kilowatt and the distance from a market, but the obvious practical difficulties in the way of taking account of these and similar factors are such as to leave the amount of power developed as the only practicable basis upon which to evaluate the power privilege. Mr. Baum says very justly that the power man who discovers a better power development than another man should have the benefit of his enterprise, and it would therefore seem to be fair that the man who discovers a power having a low development cost per kilowatt, or one near a market, should pay a less percentage of his profits to the government, as he would with a uniform government charge per kilowatt, than a man who can only find a power which must be developed at high initial cost, or which is three hundred miles from a market.

As Mr. Pinchot says:

> Any private land owner having a power site on his land would refuse to rent it for its value considered as a wood lot, but would insist on its power value as the basis of the annual rent. If his property were to be taken from him for power purposes by condemnation he would be entitled to its value for such purposes.

The principle involved has been affirmed by the Supreme Court of the United States. Why should the fact that the renter in the case we are considering happens to be the national government, make any difference? The power privilege is worth just as much to the power company whether it is secured from a private individual or from the government.

To summarize the difference between Mr. Baum's point of view and my own: he believes that water power development should be encouraged as much as possible; I believe that it should be encouraged only so much as is necessary to insure development. Beyond this the interests of the public, not those of the water power companies, should determine the government's policy.

**J. A. Britton** (by letter): I believe that the United States should grant to all bona fide hydroelectric corporations permanent rights-of-way and grants of government land without any tax whatever being made therefor, other than the cost of the land, fixed by the government on the same basis as valuation is fixed for homesteaders. Such rights, when granted, to become permanent only upon the expenditure of a sum of money representing four or five times the value of the land, and to provide therefor that upon cessation of use for a period of one year, except in case of unavoidable accident or destruction by elements of the improvements, the grant should revert to the United States.

The protection of a watershed should be a matter within the province of the United States, without imposing any tax upon the users of the land. The resultant benefits gained by the United States and the several states in which these patents would be used, and the taxes derived therefrom, are, in my opinion, sufficient to warrant the government in taking care of and protecting watersheds utilized, as such care and protection results as much to the benefit of the entire community through which the streams may flow, as it does to the company utilizing the water for power purposes. I am unalterably opposed to the levying of any tax by the state, or by the United States, where forest reserves are concerned, against enterprises of this character. To subject an investment of this kind to the whims of the legislature of any state and the Congress of the United States would be to invite confiscation of property, and would result in eventually paternalizing, and would, if neither of the above occurred, bankrupt any corporation, as it has no redress. Nor can it in California now, nor will it hereafter, be permitted to increase its rates, due to the trend of the present legislation in the matter of such close regulation of corporations. If any law is to be made, it should be a discriminatory one, choosing between the bona fide enterprises and those which are organized purely for the purpose of enriching the organizers.

I shall be very glad indeed to see a state or Coast convention held to discuss this subject. I believe it very vital to the welfare of those who have, in good faith, invested their money in water power propositions in California and other states.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29, 1908.*

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# A STUDY OF MULTIOFFICE AUTOMATIC SWITCHBOARD TELEPHONE SYSTEMS

## BY W. LEE CAMPBELL

This paper treats of three principal topics:

1. The enormous economic waste which the wire, cable, and conduit equipment of a telephone system involves.
2. A recapitulation and discussion of reasons which make this waste necessary or expedient in manually operated systems.
3. How this waste can and should be greatly reduced in systems employing automatic switchboards.

In other words, as most automatic switchboard plants have been installed in conformity with practices which emanated from experience with manual switchboard systems, the writer will discuss some of the reasons for these practices and endeavor to show that they can profitably be ignored in plans for automatic systems. To accomplish this he has made a study of the principal factors in the first cost of plants of both types, together with certain factors in their operating expenses. Since many telephone engineers have possibly not had an opportunity to study these factors, and would be much interested in a comparison of them, the writer has so arranged his data that they will be of use, not only in the discussion of his theme, but also in a determination of the measure of success which automatic switchboards have attained in furnishing the speedier, more uniform, and more economical service expected of them by the men who labored so hard and faithfully to develop them, and by the pioneers who had the courage to be their early purchasers and operators.

The first cost of a telephone plant using switchboards of either type may be divided into three principal items:

1. Cost of the apparatus (both central office and subscriber's station).

2. Cost of the central office buildings and furnishings.

3. Cost of the wire, cable, and conduit plant.

In the third item of the first cost—the wire, cable, and conduit plant—we find the largest factor of the three. The writer will not attempt, however, to give any average figures on the amount of this item. It is a variable quantity, depending in each system, not only upon the number of lines in the plant, but also upon the character of the soil, upon the average length of line as controlled by the density of population, by the form of the city, by the relative location of the business center or centers, and by obstructions, such as rivers, lakes, etc., and upon other similar conditions. Under almost any circumstances this part of the system will cost more than the two other parts combined; not infrequently it represents two-thirds of the entire first cost of the system.

It will, therefore, probably tax the credulity of engineers, whose experience has been in connection with electric power and lighting, when the writer states that in the average telephone system containing one central office only, nine-tenths of the cable and wire plant is idle—not in use for transmitting conversations, even at the peak of the load; and, too, that on the average during 24 hours' service, 98% of the wires are not in use. Yet such is the fact. Indeed, from observations made in a large number of automatic plants during the busiest hour, it was found that in offices of from 8,000 to 10,000 lines, handling a comparatively heavy traffic, the maximum number of conversations taking place at one time was equal to slightly less than 4% of the number of lines in service. As each conversation represents two lines, this would indicate a maximum of 8% of the lines engaged for conversation, operating and signaling at the peak of the load.

Excepting party-line service, which at best is but a partial remedy, there is only one method known to telephone engineers of to-day for materially reducing the great economic waste represented in the 90% of the costly cable, wire, and conduit equipment which is not in use even during the "rush hours". This method is to divide up each plant so that instead of one large central office it will employ a number of smaller offices. Just how much saving can be effected in this way, depends upon the local conditions in each city; but it will be readily understood that if small central offices or stations should be distributed over a city at the centers of well selected districts, the telephones in each district being connected only to the local station, the subscribers' lines would be decidedly shorter and cheaper than when all run for many blocks to a large centrally located office. For interconnecting between the district stations, only trunk lines would be needed, and it is necessary to have only enough of these to handle the busy-hour traffic; that is, the trunk lines need to be but a small percentage of the number of wires which would be installed if each telephone should be directly connected to one large central office.

An arrangement resembling that just outlined is in use in large cities, where of necessity some division has been made in manual systems for the reason that it is physically impracticable to terminate all lines in one multiple switchboard; that is, within the reach of each operator. Many telephone engineers do not consider it good practice to connect over 10,000 lines to one manual board, and while several boards have been installed with an ultimate capacity of 18,000 lines, the parts are so small and comparatively delicate that it is probable that repairs and depreciation will be exceedingly large items.

The writer does not wish to convey the idea that in manual practice systems are not divided up to save wire and cable; for in a very large city covering a great area this must be done. For example, in Chicago there are 15 or 16 central offices averaging about 3000 lines each. But division of an office of less than 10,000 lines is generally regarded as undesirable and to be avoided wherever possible. It is, therefore, the general practice in smaller cities to carry all or the bulk of the business on one large board, smaller branch boards being installed under sufferance and only for urgent reasons. The writer hopes to demonstrate that while this antipathy toward dividing offices of 10,000 lines or less is reasonable in manual practice, it is not reasonable in automatic practice.

Taking up the study of the factors that govern the first cost of a common-battery system of either type, and considering them in the order in which they have been named, we find first, that the cost of the ordinary direct-line, flat-rate telephone at the subscriber's station is about the same ($7.25 each) in all sizes and conditions of modern common battery manual plants, and $12.50 each in automatic plants. The cost of a private branch switchboard at a subscriber's premises is not materially affected by the size, location, or type of the central office to which it is connected. This, therefore, will not be taken into consideration.

The cost of the central office equipment when all installed in one office depends upon the number of lines entering the office, and the number of connections demanded during the busy-hour of each day. No storage feature is possible in a telephone plant. The switchboard must be designed to take care of the peak of the load, no matter how exaggerated that peak may be.

For the purpose of this paper, the writer has drawn, as shown in Fig. 1, an arbitrary curve, *A*, from which will be taken all figures used on the number of calls made per line per day in plants of different sizes. While this curve is not an unreasonable one, for flat-rate lines, it does not purport to be an exact average. Curve *B* in Fig. 1 shows the growth in the average number of lines in service and in the average number of calls per line per day in the "Chicago district" of the Chicago Telephone Company during the series of years, from 1893 to 1906. The writer supposes that the comparatively small traffic from 1893 to 1897 is largely due to the business depression then existing, and to the fact that the telephone had not then been sufficiently advertised to make it such an important factor, as it now is, in our business and social intercourse.

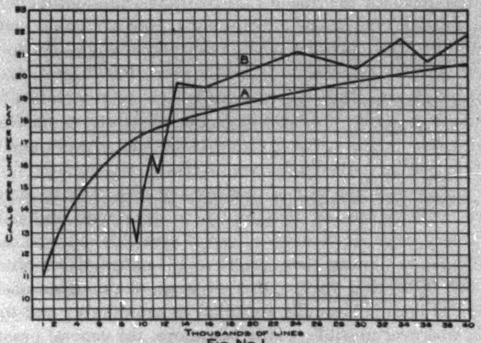

Fig. No. 1

Curve "A" Shows arbitrary number of calls per line per day, used in making comparisons.

Curve "B" Shows number of calls per line per day in Chicago district from 1893 to 1906.

It will also be taken for granted that the number of calls made during the busy hour of each day is one-eighth of the total day's business. Experience shows that this is an average ratio. The average busy-hour's work of an operator in the small manual plants is about 225 flat-rate connections; in the large manual plants about 250 flat-rate connections when no calls are trunked to other offices. In explanation of this difference in connections handled, it might be well to say that discipline is usually better in the larger offices, and consequently the operators do more work than in the smaller ones.

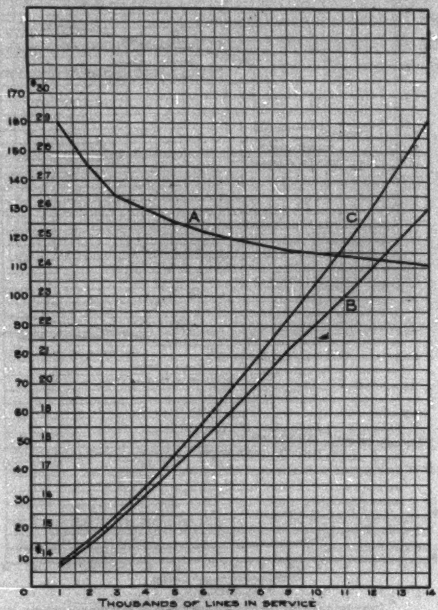

FIG. No. 2

CURVE "A" SHOWS AVERAGE NUMBER OF LINES IN SERVICE PER SUBSCRIBER OPERATORS POSITION.

CURVE "B" SHOWS NUMBER OF POSITIONS INCLUDING HOSPITAL AND LONG DISTANCE TRUNKING POSITIONS.

CURVE "C" SHOWS COST PER LINE OF ALL CENTRAL OFFICE EQUIPMENT EXCEPT LONG DISTANCE EQUIPMENT. (MANUAL OFFICES)

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With the foregoing points determined, curves *A* and *B*, Fig. 2, have been constructed. Curve *A* gives the number of flat-rate lines per operator's position, and *B* the number of operators' positions for manual switchboards equipped for from 1,000 to 14,000 lines, and for handling the number of calls per line per day indicated by curve *A*, Fig. 1. Curve *C* was then constructed, using the figures represented by curves *A* and *B* and the average prices at which a number of modern, well constructed, manual central office equipments using com-

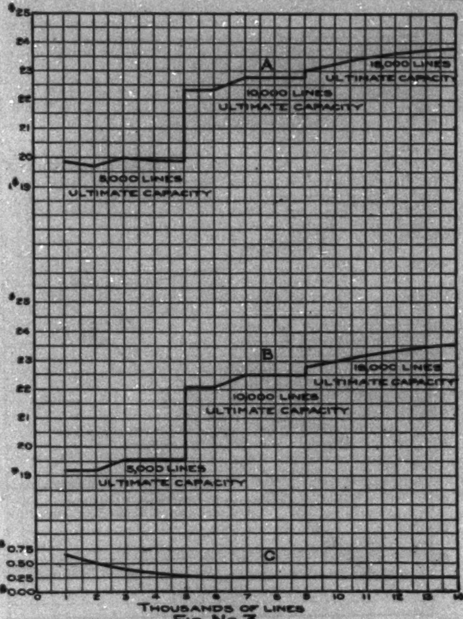

FIG. No. 3

COST OF CENTRAL OFFICE EQUIPMENT FOR AUTOMATIC OFFICES. NO TRUNKING
CURVE "A" SHOWS TOTAL COST PER LINE OF CENTRAL OFFICE EQUIPMENT INCLUDING DESKS
CURVE "B" SHOWS TOTAL COST PER LINE OF CENTRAL OFFICE EQUIPMENT EXCEPT DESKS THE COST OF WHICH IS SHOWN BY CURVE "C"
CURVE "C" SHOWS COST PER LINE OF WIRE CHIEFS, TROUBLE CLERKS, INFORMATION CLERKS AND OFFICE SUPERINTENDENTS DESKS.

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mon-battery multiple switchboards have been sold and installed.

Curve *A* in Fig. 3 gives the cost installed of automatic central office equipment for offices of from 1,000 to 14,000 lines, designed to handle the number of calls per line per day as given by curve *A*, Fig. 1. The cost of central office equipment of either type includes cost of terminal racks, power plant, wire chief's, information clerk's and trouble clerk's desks; in short, all apparatus except a long-distance board and its accessories. In making up the figures on the cost of automatic equipment, the number of trunking switches necessary per hundred lines for handling

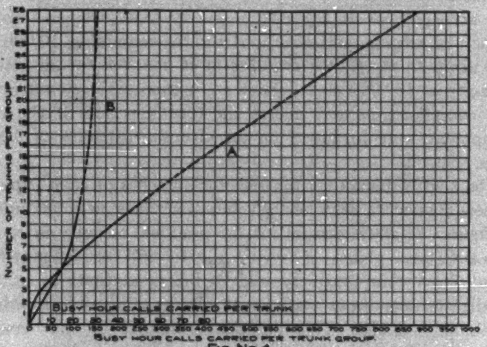

FIG NO. 4

CURVE "A" SHOWS RELATION BETWEEN NUMBER OF BUSY HOUR CALLS AND TRUNKS IN A GROUP FLAT RATE AUTOMATIC EXCHANGE CALLS AVERAGE HOLDING TIME 85 SECONDS

CURVE "B" SHOWS RELATION BETWEEN BUSY HOUR CALLS CARRIED PER TRUNK AND THE NUMBER OF TRUNKS IN THE GROUP AUTOMATIC SYSTEM, FLAT RATE CALLS.

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the busy-hour traffic was taken from curve *A*, Fig. 4. This curve, which is the result of thousands of observations made in automatic offices, follows the empirical formula:

$$\text{Trunks} = T\,C + 2.8\sqrt[3]{T\,C}$$

in which $T$ represents the length in hours of the average connection and $C$ represents the number of busy-hour calls.

For the benefit of those not familiar with automatic switchboards, the writer will state that each line terminates in what is generally called a line switch. These line switches are arranged and multiplied together in groups of 100 each. Connections between these groups are made by means of trunking switches called first selectors, second selectors, third selectors, and connectors. In a system having an ultimate capacity of 1000 lines, first selectors and connectors are the only trunking switches used. When the ultimate capacity is increased to 10,000 lines, second selectors are required also; and when the ultimate capacity is increased to 100,000 lines, third selectors are added. In a 100,000-line system, then, there is one first selector, one second selector, one third selector, and one connector for each trunk equipped.

A system with an ultimate capacity of 18,000 lines is made by installing a section of switchboard equipped for 8000 lines and arranged for an ultimate capacity of 10,000, and another section of switchboard equipped for the remaining 10,000 lines and using third-selector switches as if installed for an ultimate capacity of 100,000 lines. Such a combination does not involve any complications and makes the cost less than if the entire equipment were arranged for an ultimate capacity of 100,000 lines.

The cost of banks for ten selector switches of each type, and of ten connector switches per hundred lines, was included in all figures to allow margin for the practice, recently introduced into automatic plants, of moving selector and connector switches about from comparatively idle to busier sections in order to handle the busy-hour traffic with the least possible number of trunking switches. This practice is similar to that common in manual plants of apportioning the work among the operators' positions by means of an intermediate distributing frame.

In comparing these two first-cost curves (*C* in Fig. 2 and *A* in Fig. 3), it will be seen that the cost per line of manual equipment increases rapidly with the size of the office. This increase is principally due to the greater and greater number of multiple jacks which must be placed within each operator's reach, whereas, since the automatic is a trunking system, the cost per line is affected only by the slow growth in the number of trunks necessary to handle the busy-hour calls, and, at intervals, an increase in the ultimate capacity of the switchboard. The price of this equipment, therefore, rises more gradually and in the larger offices falls below that of the manual type.

For comparison only, the writer shows in curves *A* and *B*, Fig. 5, the respective costs of manual and automatic central office equipment as given by curve *C*, Fig. 2, and *A*, Fig. 3, plus the cost of one telephone per line.

Taking up the second item of first cost for single office systems, the writer would direct attention to Fig. 6 in which curves *A* and *B* give the square feet of floor space required on the average for automatic and manual central office equipments respectively. Curve *C* gives the cubic feet of space required for automatic equipment, and curve *D* gives the cubic feet of space required for manual equipment. In this same figure, curve *E* for automatic

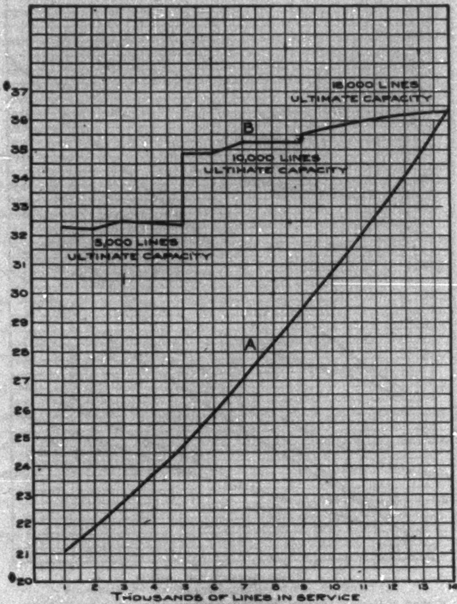

FIG. NO. 5

COMPLETE COST OF CENTRAL OFFICE EQUIPMENT EXCEPT LONG DISTANCE BOARD PLUS COST OF ONE TELEPHONE PER LINE.

CURVE "A" IS FOR MANUAL OFFICES.

CURVE "B" IS FOR AUTOMATIC OFFICES.

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equipment and curve *F* for manual equipment give the first cost of the necessary space in fire-proof buildings at an estimated rate of 19 cents per cubic foot for housing the automatic and manual equipments indicated. The cost of furnishings

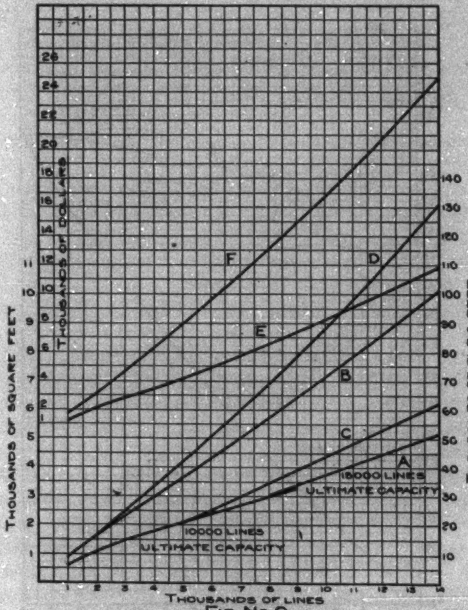

FIG. No. 6

CURVE A SHOWS SQUARE FEET OF FLOOR SPACE REQUIRED FOR AUTOMATIC CENTRAL OFFICE EQUIPMENT (NO TRUNKING)
CURVE "B" SHOWS FLOOR SPACE REQUIRED FOR MANUAL EQUIPMENT (NO TRUNKING)
CURVE "C" SHOWS CUBIC FEET OF SPACE REQUIRED FOR AUTOMATIC EQUIPMENT.
CURVE "D" SHOWS CUBIC FEET OF SPACE REQUIRED FOR MANUAL EQUIPMENT
CURVES "E & F" SHOW COST IN DOLLARS OF BUILDING SPACE REQUIRED FOR AUTOMATIC AND MANUAL EQUIPMENTS RESPECTIVELY. FIRE PROOF BUILDINGS ESTIMATED COST 19 CENT PER CUBIC FOOT.

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and land, and cost of space used for executive offices, storage, etc., are not included, nor is the cost of space usually allowed for a growth of at least 20% or 25% in switchboards included. The figures do, however, include the cost of space for operators' rest rooms, hospital, dining room, kitchen, etc.

It will be noted that the cost of building space for automatic equipment is considerably less than that for manual equipment, and that for offices of over 5000 lines the automatic occupies about half the space required for the manual. No effort has been made to secure comparative figures on the cost of furnishings, but they are unquestionably more expensive in manual offices, since here recreation and rest rooms, restaurant, kitchen, etc., are commonly furnished and equipped for the use of the operators. In automatic offices the number of employees

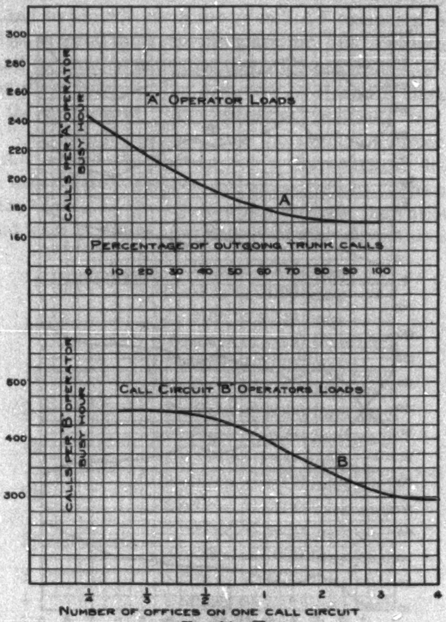

FIG. NO. 7
OPERATOR'S LOADS

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is comparatively small and the men are in the majority, consequently, it is not customary to make any elaborate provision for their comfort when off duty.

Having now shown what the average costs of the central office equipments and buildings would be in single office plants

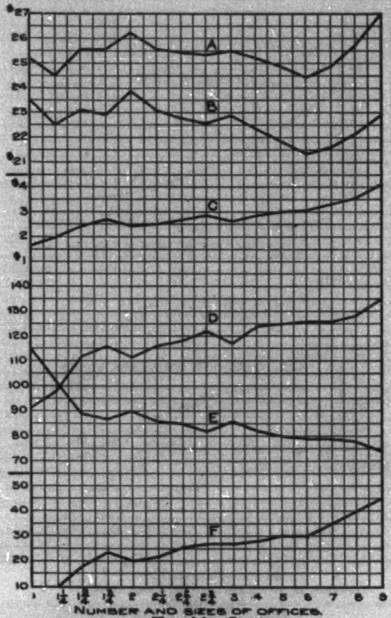

FIG. NO. 8

STUDY OF 10,000 LINE SYSTEM WITH VARIOUS NUMBERS AND SIZES OF MANUAL OFFICES
ESTIMATED 173,500 CALLS PER DAY ESTIMATED 21,687 CALLS DURING BUSY HOUR
CURVE "A" SHOWS COMBINED COSTS OF CURVES "B" AND "C"
CURVE "B" SHOWS COST PER LINE OF CENTRAL OFFICE EQUIPMENT
CURVE "C" SHOWS COST PER LINE OF BUILDING SPACE REQUIRED FOR CENTRAL OFFICE EQUIPMENT FIRE-PROOF BUILDINGS ESTIMATED COST 15 CENTS PER CUBIC FOOT
CURVE "D" SHOWS NUMBER OF "A" OPERATORS POSITIONS REQUIRED AT ALL OFFICES.
CURVE "E" SHOWS THE AVERAGE NUMBER OF LINES SERVED BY EACH "A" OPERATOR'S POSITION
CURVE "F" SHOWS TOTAL NUMBER OF "B" OPERATOR'S POSITIONS.

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handling the traffic indicated by curve *A*, Fig. 1, it is next in order to see what effect dividing up a system so that it employs more than one office, has on these two items of first cost.

In manual systems an operator's daily quota of connections is reduced when part of the calls which she handles must be trunked to other offices. This effect of trunking on the operator's work is indicated by curve *A*, Fig. 7, which gives the number of flat-rate busy-hour connections which one of the largest manual operating companies has found that an average "A" operator will make with various percentages of trunked calls. It is, therefore, necessary in a multi-office manual system to install and to provide space for more "A" operators' positions, as well as to install and provide space for "B" operators' positions and to provide increased space for rest rooms, etc.

As an illustration, in Fig. 8, curves *D*, *F*, and *E* show respectively the number of "A" operators' positions, the number of "B" operators' positions, and the average number of lines per "A" operator's position for a hypothetical 10,000-line system with different numbers and sizes of offices. The numerals along the bottom of the figure which indicate the various numbers and sizes of offices, have the following significance:

| | | |
|---|---|---|
| 1¼ | represents | 1 office of 8000 lines<br>1 office of 2000 lines |
| 1²⁄₄ | " | 1 office of 6700 lines<br>2 offices of 1650 lines each |
| 1¾ | " | 1 office of 5725 lines<br>3 offices of 1425 lines each |
| 2 | " | 2 offices of 5000 lines each |
| 2¼ | " | 2 offices of 4450 lines each<br>1 office of 1100 lines |
| 2²⁄₄ | " | 2 offices of 4000 lines each<br>2 offices of 1000 lines each |
| 2¾ | represents | 2 offices of 3650 lines each<br>3 offices of 900 lines each |
| 3 | " | 3 offices of 3333 lines each |
| 4 | " | 4 offices of 2500 lines each |
| 5 | " | 5 offices of 2000 lines each |
| 6 | " | 6 offices of 1667 lines each |
| 7 | " | 7 offices of 1429 lines each |
| 8 | " | 8 offices of 1250 lines each |
| 9 | " | 9 offices of 1111 lines each |

It will be noted that the number of "A" and the number of "B" operators' positions grows quite rapidly as the number of offices is increased, while the number of lines per "A" operator's position diminishes.

In working out these curves the percentage of outgoing trunk calls from any office was calculated by the formula; trunking% = $100 \frac{A-B}{A}$ multiplied by 0.75; where $A$ is the total number of lines in the system, $B$ equals the number of lines in the office under consideration and 0.75 is a factor which experience in-

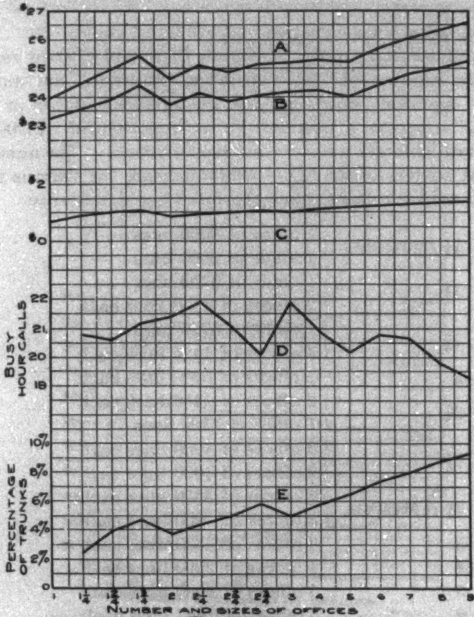

FIG. NO. 3

STUDY OF 10,000 LINE SYSTEM WITH VARIOUS NUMBERS AND SIZES OF AUTOMATIC OFFICES
ESTIMATED 173,500 CALLS PER DAY. ESTIMATED 21,687 CALLS DURING BUSY HOUR.
CURVE "A" SHOWS COMBINED COSTS OF CURVES "B" AND "C"
CURVE "B" SHOWS COST PER LINE OF CENTRAL OFFICE EQUIPMENT
CURVE "C" SHOWS COST PER LINE OF BUILDING SPACE REQUIRED FOR CENTRAL OFFICE EQUIPMENT
CURVE "D" SHOWS THE AVERAGE NUMBER OF BUSY HOUR CALLS CARRIED PER TRUNK LINE BETWEEN OFFICES.
CURVE "E" SHOWS THE RATIO OF THE TOTAL NUMBER OF TRUNK LINES BETWEEN ALL OFFICES TO THE 10,000 SUBSCRIBER'S LINES ENTERING ALL THE OFFICES OF THE SYSTEM.

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dicates will allow under average conditions for the community of interest between the subscribers in an office district. Of course, in a study of a particular locality this factor should, if possible, be accurately determined; it may be as small as 0.4 or as large as 1.5.

Curve *B*, Fig. 8, gives the approximate cost per line of the central office equipments installed as derived from the data used in curves *D*, *F*, and *E* previously mentioned. It will be noted that although more positions are necessary than in a single office, the cost of each position is reduced by a decrease in the line equipment and in the number of multiple jacks per position, so that there is not a great variation in the total switchboard cost. In the same Fig. 8, curve *C* shows the cost per line of the buildings for the various sizes and numbers of offices in the divided system. The cost of space required for executive offices, storage, etc., is not included in these figures, nor do they include the cost of land and furnishings. Curve *A* shows the combined cost per line of central office equipment and buildings. It will be noted that the greater cost of buildings is, to some extent, counterbalanced by a reduction in the cost of the equipment. The small increase would in any event be of little moment in comparison with the saving in the cost of the wire, cable, and conduit plant, which might be secured by plant division. It would, therefore, appear that we must look further for the cause of the objections to multi-office manual systems.

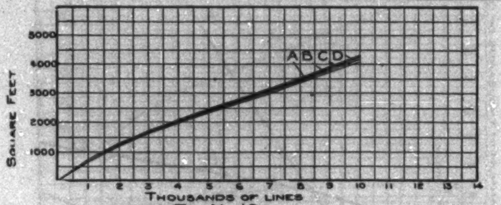

FIG. No. 10

CURVE "A" SHOWS FLOOR SPACE REQUIRED FOR AUTOMATIC CENTRAL OFFICE EQUIPMENT OF 100 000 LINES ULTIMATE CAPACITY. NO INCOMING OR OUTGOING TRUNK EQUIPMENT.

CURVE "B" SAME AS "A" EXCEPT SPACE ADDED FOR EQUIPMENT FOR 25% EACH OF INCOMING AND OUTGOING TRUNK CALLS.

CURVE "C" SAME AS "A" EXCEPT SPACE ADDED FOR EQUIPMENT FOR 50% EACH OF INCOMING AND OUTGOING TRUNK CALLS.

CURVE "D" SAME AS "A" EXCEPT SPACE ADDED FOR EQUIPMENT FOR 66% EACH OF INCOMING AND OUTGOING TRUNK CALLS.

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Before discussing operating expenses, however, let us see what effect plant division has on the first cost of automatic central office apparatus and buildings. To illustrate the effect, the curves in Fig. 9 have been worked out, using the same 10,000-line system and the same numbers and sizes of offices employed in Fig. 8 for the manual system. The cost, installed, of central office equipment is somewhat increased by division, as will be noted by reference to curve *B*. The central office space required is also greater, as shown by curve *C*, Fig. 9, and by curves *A*, *B*, *C*, and *D*, Fig. 10. The slow increase in the combined cost of equipment and building as more offices are added is shown by curve *A*, Fig. 9. The increases are of small import in comparison with the saving in the underground and aerial construction secured by using a larger number of offices.

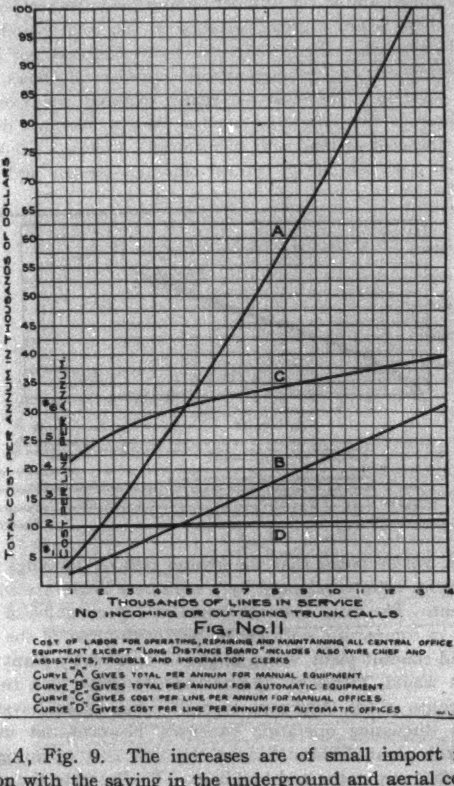

FIG. NO. 11

COST OF LABOR FOR OPERATING, REPAIRING AND MAINTAINING ALL CENTRAL OFFICE EQUIPMENT EXCEPT "LONG DISTANCE BOARD" INCLUDES ALSO WIRE CHIEF AND ASSISTANTS, TROUBLE AND INFORMATION CLERKS

CURVE "A" GIVES TOTAL PER ANNUM FOR MANUAL EQUIPMENT
CURVE "B" GIVES TOTAL PER ANNUM FOR AUTOMATIC EQUIPMENT
CURVE "C" GIVES COST PER LINE PER ANNUM FOR MANUAL OFFICES
CURVE "D" GIVES COST PER LINE PER ANNUM FOR AUTOMATIC OFFICES

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Taking up the subject of operating expenses, the writer would direct attention first to curves *A* and *C*, Fig. 11, which show average annual operating and maintenance labor cost for manual central offices of from 1000 to 14,000 lines, doing no trunking and handling the number of calls per line per day indicated by curve *A*, Fig. 1. Curves *B* and *D*, Fig. 11, show respectively the total annual cost and the annual cost per line of all central office labor for automatic offices of from 1000 to 14,000 lines. These figures are averages of the labor costs obtained from a considerable number of automatic switchboard operating companies.

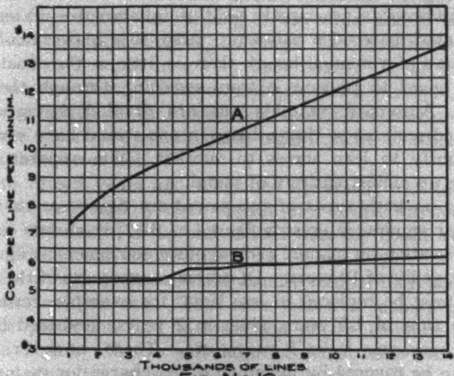

Fig. No. 12

Curve "A" Shows cost per line per annum for operating manual central office as shown by curve "C" Fig 11 plus cost of power, lighting and interest, depreciation, taxes and insurance on central office equipment and on central office building

Curve "B" Same as "A" but for Automatic equipment (See curve "D" Fig. 11)

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The writer would next direct attention to curves *A* and *B*, Fig. 12, which give the central office labor expense as shown in Fig. 11, plus the cost per line per annum of certain central office equipment and central office building charges that are materially affected by plant division. Curve *A* is for manual offices of from 1000 to 14,000 lines, no trunking, and curve *B* gives similar data for automatic offices. These figures include insurance, taxes, interest and depreciation on central office equipment and buildings, renewals for central office equipment, and the cost of lighting and power.

Insurance of the central office equipment in fire-proof buildings is taken at 1% per annum. Although several companies operating automatic apparatus have informed the writer that they secured a lower rate than that which they could get on manual equipment, it does not appear that the rating authorities have made any general rule which would assure a reduction. Since, however, much of the damage done to switchboards by fire is caused by blazes originating within the apparatus itself, and since the insurance companies exempt themselves from losses caused by such blazes, it would seem that fire losses would be smaller with automatic equipment than with manual. Manual switchboards are largely built of inflammable material and are incased in wooden cabinets. Also, if a blaze should start in one end of a manual board, there is little in the construction of the board to prevent it from sweeping through the entire length. Automatic switchboards are divided up into small separated sections so that a blaze in one would have very little opportunity to leap across to another. The apparatus itself is made up almost entirely of metal.

Taxes on both types of equipment are figured at the rate of 1.5% per annum; interest is figured at 6% per annum for both.

Depreciation on manual central office equipment is figured on an average life of 10 years. Of course, many parts of the switchboard must be replaced in less time: for example, cords in an average time of 1.5 years, plugs in 2 years, keyboard lamps 3 years, answering jacks 5 years, etc. These, however, are believed to be covered by including a 2% charge for maintenance materials and renewals. Depreciation on automatic equipment is calculated on a life of 12 years. Although no automatic plants, to the best of the writer's knowledge, have been in continuous service for this length of time, he has found that plants which have been in operation for 7 or 8 years show very little wear. While some such plants have been replaced by new ones, it has been because it was believed that better service and decreased operating costs, made possible by the new and improved equipment obtainable at the time the change was made, would pay for making it before the life of the original plant was exhausted. As an example, showing the effect of wear and tear on an automatic switchboard, there is in Fall River, Mass., an automatic plant which has been in operation for 7 years; at this plant the only appreciable wear is on the shaft wipers of the busier trunking switches. While these wipers could be renewed at a very modest expense they will apparently last for some years yet. The wear on the equipment, which is individual to each subscriber's line, is hardly noticeable. In fact, an automatic switchboard has never been known to wear out, while manual switchboards are really worn out by the continued use of the parts by the operators. As the writer has already stated, such manual switchboard parts as cords, keyboard lamps, answering jacks, trunk jacks, etc., will need to be replaced at intervals during the life of the board. It is also found that the keyboards and plug shelves made of wood and sole leather become so worn from the continual contact of the operators fingers and the rubbing of the cords, and so battered by the constant pounding of the plugs, that they must be replaced in 6 or 7 years on a very busy board. In 10 years, or sometimes even less, the keys, multiple jacks, multiple cables, etc., are generally in such condition that it becomes necessary to replace the entire switchboard, regardless of whether it has become obsolete or not.

Ten to fifteen years ago telephone apparatus was being developed so very rapidly that the life of a board was not more than 5 or 6 years. At the end of that time the board would be so out-of-date that competition or a proper regard for service or for operating expenses would usually compel its replacement by a more modern one. That time ended in manual practice with the perfection and introduction of the common-battery multiple board. No radical improvements have since been made. Automatic switchboards have also reached a somewhat similar plane of development. For illustration, in the Fall River system installed in 1901, a subscriber makes a call by means of a dial, and secures service very similar to that in the most modern plant. Looking at the automatic switchboard itself, we find the so-called grouping system, the automatic selection of trunks, push-button ringing, and other essential features of the latest equipment. It is true that great improvements have been made in automatic equipment in very recent years, such as the introduction of common-battery service, party lines, line or individual switches, improved methods of manufacture, installation, etc., but these are all points which appeal to the manufacturer or to the operating company, while improvements in the general appearance of the telephones are about the only ones made in the last 7 or 8 years which are of much interest to the telephone users. Therefore, considering service only, and viewing the matter from the standpoint of the telephone subscriber, the writer believes it reasonable to conclude that there is little probability, in the near future, of a manual switchboard being rendered obsolete by a more improved manual board or of an automatic switchboard being put out of the arena by an automatic switchboard giving better service. He, therefore, has taken the life of a manual switchboard at the full amount that a consideration of wear and tear only will permit; and, in order to be perfectly conservative, has placed the life of an automatic board at but 2 years longer although there is no reason to suppose that it would not still be good for a number of years of service at the end of that time. The amount which must be set aside annually at 6% compound interest to equal 100% in 12 years is 6% of first cost. Therefore, this percentage is used in calculating depreciation on automatic central office equipment, while for manual equipment the depreciation charge is taken at 7.5%, which is the amount which must be set aside annually at 6% compound interest to equal first cost in 10 years.

Looking into the matter of maintenance material or renewals for automatic central office equipment, the writer has found from an investigation of a number of automatic plants that the renewals for the switchboard proper amount on the average to 0.2% per annum on the first cost of the central office equipment. The power plant, main distributing frame, and other parts of the central office equipment, increase the renewals item, however, and in order to cover everything it has been taken at 0.5% for automatic offices.

The cost of power per originating call handled is about twice as much for automatic switchboards as for most of the manual switchboards used by the "independent companies". The amount of current consumed is almost the same, 0.006 of an ampere-hour. Automatic plants generally use a battery of 46 volts, about twice the voltage of the usual manual battery, although in large plants where the lines are long, 40-volt batteries are sometimes employed in manual practice. The manual switchboards generally used by the Bell companies require considerably more current than those used by the independent companies. The amounts used by the independent boards have been taken in working out the curves in this paper. Taking the cost of power, transformed and delivered at the switchboards, at 15 cts. per kilowatt-hour gives a cost of $0.0216 per thousand local calls for manual offices and of $0.0432 per thousand local calls for automatic offices. The additional cost per thousand incoming trunk calls received at a manual office would be $0.0144. For automatic offices the additional cost for incoming trunk calls would be $0.004 per thousand, assuming that the number of calls trunked out from an office equals the number incoming.

The cost of lighting automatic central office equipment has been taken at $4.00 per thousand lines per month; and for manual offices the cost of lighting the operators' positions, the switchboard rooms, operators' retiring rooms, terminal room, desks, etc., has been taken at $2.00 per switchboard position per month.

The annual charges on the central office buildings have been taken at the same rates for the two systems; that is, insurance on fire-proof central office buildings has been figured at 0.5% per annum, interest at 6%, taxes at 1%, and depreciation and repairs at 2% per annum.

In order to illustrate the effect on the annual expenses, just discussed at length, caused by dividing a system up so that it employs a number of offices instead of one, the writer has constructed the curves in Fig. 13, which show what the expenses would be for the different numbers and sizes of offices in the hypothetical 10,000-line system used in Figs. 8 and 9. Referring to curve *A* in Fig. 13, it will be noted that the annual cost of central office labor for the nine-office arrangement of the manual system is 80% greater than for the single office arrangement.

It might be stated just here that the item of operators' hire is one which yearly grows to greater magnitude. One very large telephone operating company instructs its engineers engaged in development studies to estimate on operators salaries being at least 15% higher 15 years hence.

Curve *B*, Fig. 13, shows that the increase in the cost of labor plus the annual charges on equipment and buildings, weighs heavily against the division of manual systems. In fact, experience shows that where the ultimate number of subscribers that may be expected in an office district within fifteen years does not exceed the capacity of a single multiple board (about 10,000 lines) and there is no concentrated group of subscribers at a considerable distance from the best location for a single office, it is generally found that a one office system will be the most economical when manual equipment is used.

There are conditions under which it is profitable to divide manual 10,000 line plants; that is, there are conditions under which the saving in the annual charges on cable, wire and conduit, will more than offset the increase in central office expenses, if division is not carried too far. It is, of course, necessary to make a thorough engineering study of each apparently suitable location for a branch office, to determine whether or not any real economy would result; but since the annual charges on subscribers' lines less than two miles long using No. 22 gauge

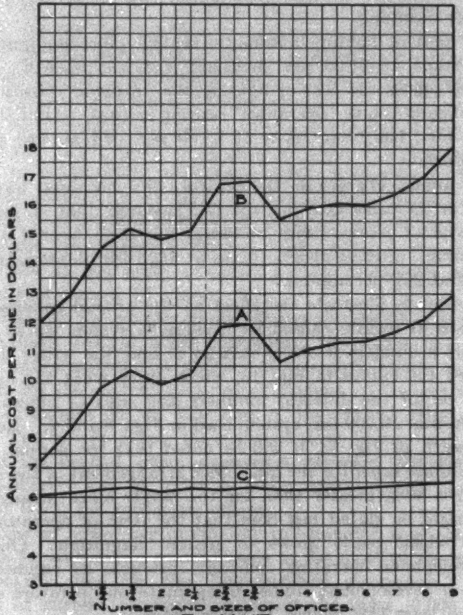

FIG. No. 13

CURVE "A" GIVES ANNUAL EXPENSE PER LINE OF ALL CENTRAL OFFICE LABOR FOR A 10,000 LINE MANUAL SYSTEM WITH DIFFERENT NUMBERS AND SIZES OF OFFICES THE SAME AS USED IN FIG 8.

CURVE "B" SHOWS LABOR COST AS GIVEN BY CURVE "A" PLUS INTEREST, TAXES, DEPRECIATION MAINTENANCE AND INSURANCE ON MANUAL CENTRAL OFFICE EQUIPMENT AND ON CENTRAL OFFICE BUILDINGS, ALSO PLUS COST OF LIGHTING AND POWER.

CURVE "C" SHOWS FOR A 10,000 LINE AUTOMATIC SYSTEM (SEE FIG 9) THE SAME ITEMS AS THOSE GIVEN IN CURVE "B" FOR A LIKE MANUAL SYSTEM.

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cable conductors average about $2.50 per mile, it will be seen that the saving in length of line will be less than the corresponding increase per line per annum in central office expenses (indicated by curve " B " in Fig. 13) except where the lines are comparatively long. Roughly speaking, an economical arrangement of the average divided manual system will include offices not much less than two miles apart.

Curve *C* in Fig, 13 shows that division of automatic systems may be profitably carried much further on account of the slow increase in central office expenses resulting from adding to the number of offices.

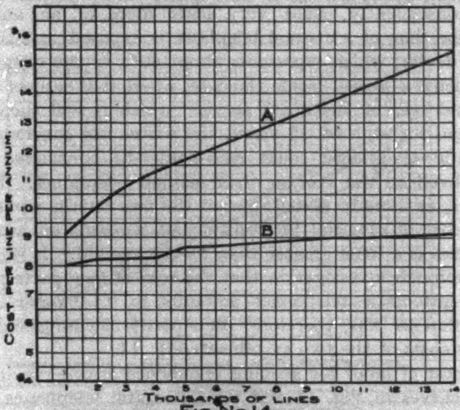

FIG. NO. 14

CURVE "A" SHOWS COST PER LINE PER ANNUM OF MANUAL CENTRAL OFFICE AND CENTRAL OFFICE BUILDING EXPENSES (SEE CURVE "A" FIG. 12) PLUS INTEREST, DEPRECIATION AND TAXES ON ONE TELEPHONE PER LINE AND PLUS COST OF CLEARING LINE AND TELEPHONE TROUBLE

CURVE "B" SHOWS COST PER LINE PER ANNUM OF AUTOMATIC CENTRAL OFFICE AND CENTRAL OFFICE BUILDING EXPENSES AS GIVEN BY CURVE "B" FIG. 12 PLUS INTEREST, DEPRECIATION, TAXES AND CALLING DEVICE REPAIRS ON ONE TELEPHONE PER LINE AND PLUS COST OF CLEARING LINE AND TELEPHONE TROUBLE.

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The writer hopes that he will be pardoned if, before leaving the subject of operating expenses, he pauses to call attention to curves *A* and *B*, Fig. 14, which include the office expenses as given by curves *A* and *B*, Fig. 12, plus the annual cost per line of clearing line and telephone trouble, and plus the annual charges for interest, depreciation, and taxes on one telephone per line.

In calculating depreciation, the lire of the telephones for both systems has been taken to be 10 years. It might appear unreasonable at first thought to believe that the more complicated automatic telephone has as long a life as the simpler manual instrument, but experience shows that the parts of a telephone which depreciate most rapidly are those which are handled by the user, knocked and rubbed against by passers-by and mischievous persons; also that the parts which must be kept highly finished, because they are exposed to view, are most quickly affected not only by human contact but by sunshine, dampness, etc. Consequently, since very little more of an automatic telephone than of a manual telephone is exposed, and since the calling device, which represents about 40% of the value of the instrument, is locked inside the case, where it is subject only to wear and tear of legitimate service, which it will successfully withstand for at least 15 years, the writer has concluded that automatic telephones could reasonably be considered to be longer lived on the average than manual telephones. He has, however, as already stated, placed the two on the same basis.

The cost of material for repairs and renewals on automatic telephones is a little greater than for the manual. It was found by a thorough investigation that the cost of new parts peculiar to the automatic telephones amounts to 0.14% per annum. This difference has, therefore, been noted in comparing maintenance costs of the two systems in Fig. 14.

The cost of labor for keeping telephones in order is included in the curves in Fig. 14 and for automatic telephones is also shown separately in Fig. 15. No insurance on the telephones is included.

Returning to the subject of plant division and its results, there is still another point to be considered, namely, the effect of plant division on service. An investigation of this reveals what is a very serious objection to a multi-office manual system; because slower service, more mistakes by the operators, and, what is most aggravating to a telephone subscriber, more premature disconnections during conversation, are the inevitable results of having connections handled by two operators instead of by one. The good will of the telephone user is something which cannot be lightly considered in these days of keen telephonic competition. Unpopular service is not only a serious handicap in a contest with a rival company; but it also retards growth, invites higher taxes and hostile legislation, and often results in a general clamor for the regulation and reduction of rates. On the other hand, a record of giving service which meets with the general approval of its subscribers is an asset of inestimable value to any telephone operating company, and, in fact, is the best reason for the company's existence. We find, therefore, telephone managers, who are chiefly concerned in pleasing the public, pretty solidly arrayed against having manual systems split up, except where the number of stations is so great or the area covered by the system so large that rates would be excessive if one central office only were used. In fact, "no divided systems," was one of the battle cries of the leaders of the independent telephone movement which has spread over the country so rapidly and so widely that its present magnitude baffles conception.

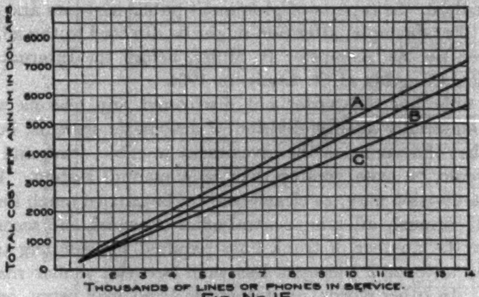

FIG. No. 15

COST OF LABOR FOR CLEARING TROUBLE IN AND MAINTAINING PHONES AND OF CLEARING LINE TROUBLES.

CURVE "A" SHOWS LABOR COST FOR CLEARING AUTOMATIC PHONE TROUBLE WITH RELATION TO TOTAL NUMBER OF PHONES IN SERVICE. (AUTO. C. B. SYSTEM)

CURVE "B" SHOWS LABOR COST OF CLEARING LINE TROUBLE WITH RELATION TO THE NUMBER OF LINES IN SERVICE. (AUTOMATIC SYSTEM)

CURVE "C" SHOWS LABOR COST OF CLEARING LINE TROUBLE WITH RELATION TO THE NUMBER OF PHONES IN SERVICE. (AUTOMATIC SYSTEMS)

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Increasing the number of offices in an automatic system does not appreciably affect the service. All calls are trunked anyhow, whether one office is used or many. Therefore, splitting up such a system does not add to the amount of trunking or in any way affect the speed and uniformity of service. The subscriber is not required to change his method of calling or to make more turns of his dial. No more automatic switches are necessary and a connection does not include any more switches in a divided system than in a single office plant. When the writer states that the service of a multi-office automatic system is on a par with that of a single office automatic system, he believes that he gives it the highest endorsement possible in the present state of the telephone art; for the companies operating automatic switchboards have demonstrated beyond question that they can give satisfactory service and furnish any special attention to which patrons of the girl-operated systems have been accustomed. Indeed, telephone users, who have had experience with both, almost universally prefer the automatic service to the manual. This fact is not only attested by all who have made an investigation, but has been publicly affirmed repeatedly in the reports of prominent public servants and engineers. For example, attention might be directed to the address delivered by Mr. Kempster B. Miller, before the International Electrical Congress at St. Louis, in 1904.

Not only has the writer not discovered any reasons which weigh materially against division of automatic systems, but he finds that the saving in the investment in cable, wire, and conduit would be even greater than in a manual system. First, because division may, as clearly shown, be carried much further without seriously affecting central office expenses, and secondly, because the number of trunk lines required for handling traffic between automatic offices is less than between similar manual offices. In other words, an automatic trunk will carry, on the average, more busy-hour calls than a manual trunk.

Curve *A*, Fig. 16, shows the call-carrying capacities which one of the largest manual telephone companies instructs its engineers to use in arriving at the number of trunks needed between proposed offices. As a rule, a manual trunk should not be expected to handle over 15 to 18 calls during the busy-hour even between rather large, well-managed offices; between small offices from 10 to 12 is all that can safely be depended upon. Reference, however, to curves *A* and B, Fig. 4, shows that between automatic offices a considerably higher trunk-carrying capacity is experienced. The largest number of trunks per group almost universally used in automatic systems is 10. Therefore, the curves in Fig. 4 are dotted above the line corresponding to 10 circuits per group. With groups of this size a minimum carrying capacity of 22.5 busy-hour calls per trunk is secured. This is a decided increase over the carrying capacity of manual trunks even where the latter are installed in groups of the greatest efficiency; that is, groups of about 73 circuits each. It would rarely, if ever, be possible to obtain such a large group if a manual plant were so divided that all offices were comparatively small, but in almost any multi-office system the majority of the trunks between offices can readily be placed in small groups of 10 trunks each. Consequently, in an automatic multi-office system maximum efficiency is secured on nearly all of the trunks. This is illustrated by curve *D*, Fig. 9, which gives the average minimum carrying capacity per trunk for each of the different arrangements of the hypothetical 10,000-line system. The average minimum number of busy-hour calls carried per trunk is, according to the curve, about 20.75, and the lowest figure is 19.3 for the nine office arrangement. Sup-

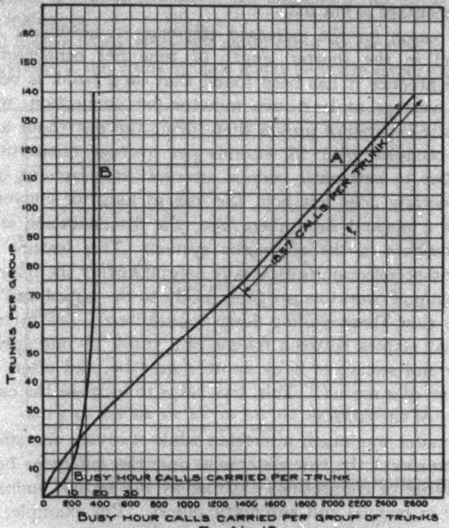

FIG. NO. 16

CURVE A SHOWS RELATION BETWEEN NUMBER OF FLAT RATE CALLS AND CIRCUITS IN THE GROUP. LOCAL "B" TRUNKS AVERAGE HOLDING TIME 2 MINUTES. MANUAL SYSTEM

CURVE "B" SHOWS RELATION BETWEEN THE NUMBER OF CIRCUITS PER GROUP AND THE NUMBER OF BUSY HOUR CALLS CARRIED PER CIRCUIT

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posing, for the moment, that it be practicable to use this nine-office arrangement in a 10,000-line manual system, the average number of busy-hour calls carried per trunk would be about 12.

The small number of trunks that will carry the traffic between automatic offices even in a thoroughly divided system is illustrated by curve *E*, Fig. 9, which shows the ratio on a percentage basis between the number of trunks and the number of subscribers' lines. With the largest number of offices considered this percentage is but 9.3.

One reason for the increased efficiency of automatic trunks is found in the shorter length of time per connection. In manual practice it has been found that each trunk is occupied on the average at least two minutes per connection, whereas automatic experience proves that during the busy-hour a trunk is not occupied over 83 seconds per average connection. A subscriber to automatic service answers his telephone quicker and generally does not hold the line so long for conversation as does a manual subscriber; also, the disconnection is made much quicker in the automatic system. This feature of the quicker disconnection is especially helpful during the busy hours when manual operators are most likely to be rushed and consequently slow about pulling down connections. The interval of time that elapses between release of a trunk by one automatic selector and seizure of it by another need be, and often is, but a fraction of a second. This, too, helps to increase the carrying capacity of the trunks.

The writer was much interested while studying the efficiency of the trunks of the two systems to note the difference between the number of connections existing at the busiest moment of the day in manual and automatic offices. For example, in the central office of a busy manufacturing city in Ohio a count was taken every day for a week in January of one year to ascertain the maximum number of connections "up" in the various operators' positions at intervals during the busy hours of each day. The results for the busiest day are shown in curve *A*, Fig. 17. A few months after these observations were made the equipment of this office was changed to the automatic type. In the following January, one year after the original data were secured, counts were made every day for one week of the number of connections "up" during the busy hours in the automatic switchboard. The results for the busiest day are shown in curve *B*, Fig. 17. It will be noted that the maximum percentage of connections counted at one time on the manual was 7 while on the automatic it was but 4.36. Similar observations were made on a number of automatic plants, and, as already stated earlier in this paper, it was found that in busy automatic offices of 8000 or 10,000 lines, the maximum number of connections counted at the busiest moment did not exceed 4%. In small offices of less than 1000 lines where erratic fluctuations of the traffic are more noticeable the maximum ran up to 4.7% in some instances.

A still higher trunk efficiency could often be secured in automatic systems if the trunk groups could be made larger than 10 lines each without impairing the speed at which idle trunks are selected. This is shown by the dotted portions of curves *A* and *B*, Fig. 4, which give the carrying capacity per group and per circuit for groups up to 28 circuits each. On account of the fact that in an automatic system where the number of offices is comparatively large, and each office is comparatively small, the trunks are generally divided into a large number of small groups, and it is doubtful if there would be anything gained by making the maximum size of a group of trunks between offices greater than 20 circuits. Indeed in such a system many of the groups would contain considerably less than 20 circuits each.

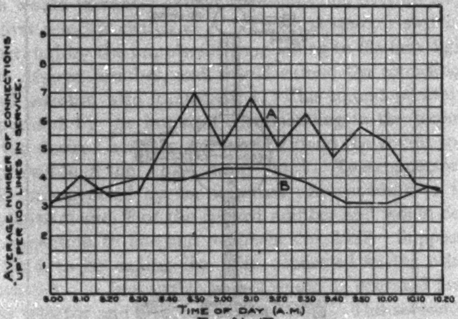

FIG. No.17

CURVE "A" IS FOR A MANUAL OFFICE OF 2000 WORKING LINES AND 3082 TELEPHONES

CURVE "B" IS FOR THE SAME OFFICE WITH 2238 WORKING LINES AND 3112 TELEPHONES ONE YEAR LATER AND AFTER AUTOMATIC EQUIPMENT HAD BEEN INSTALLED.

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The manufacturers of automatic apparatus have recognized the possibilities of larger groups and are now testing equipment designed to enable them to put more lines in each. Since such equipment has not come into general use, however, it will not be considered further in this paper.

In endeavoring to form some conception of the methods used for introducing trunking of calls on a large scale between automatic offices, it is well to understand the difference between two general types of office that are being used for this purpose.

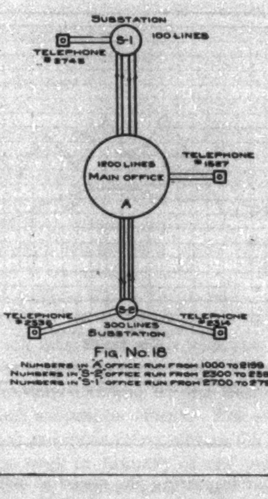


FIG. No. 18
NUMBERS IN "A" OFFICE RUN FROM 1000 TO 2199
NUMBERS IN "S-2" OFFICE RUN FROM 2300 TO 2599
NUMBERS IN "S-1" OFFICE RUN FROM 2700 TO 2799

One is known as a "sub-station" or "district" office and the other as a "branch" office. The difference lies in that a sub-station contains line switches and connector switches but no apparatus for making local connections; that is, every originating call is trunked to a distant larger office containing the selector switches, whereas a branch office contains switches of all classes and completes within itself all local connections demanded. It will readily be seen, therefore, that a sub-station requires more outgoing and incoming trunks than a branch office.

For an illustration of a system using sub-stations attention is directed to Fig. 18, in which *A* represents a " main " office containing the equipment for 1200 lines. " A " contains also the first selector and second selector switches used by two substations *S*-1 and *S*-2. *S*-1 is represented as containing line switches and connector switches for 100 lines and *S*-2 is supposed to contain line switches and connector switches for 300 lines.

Calls would be handled as follows: suppose for example, a subscriber at telephone No. 2314, which is connected to substation *S*-2, to be calling No. 1527 connected to the main office *A*. The impulses sent over the circuit through the calling device of telephone No. 2314, would first operate a line switch at *S*-2, which would instantly extend the connection over an idle trunk to a first selector switch at *A*. This first selector switch would be operated by the impulses corresponding to the first digit " 1 " of the desired number, and, would extend the connection to a second selector, also located at *A*. This second selector would be operated by the impulses corresponding to the second digit 5 of the desired number and would extend the circuit to a connector switch in the " 1500 group " at *A*. This connector switch would be operated by the impulses corresponding to the last two digits 2 and 7 of the desired number and would complete the connection to line and telephone No. 1527. Suppose again No. 2314 to be calling No. 2745 connected to the other substation *S*-1. A line switch at *S*-2 would be operated first, then a first selector and a second selector at *A*. This second selector would extend the connection over a trunk to a connector switch located at *S*-1. This switch would be operated by the impulses corresponding to the last two digits of the desired number, and would complete the connection to line and telephone No. 2745.

Suppose again, No. 2314 to be calling No. 2536 connected to the same sub-station, *S*-2. In this case, a line switch at *S*-2 would, as before, extend the connection to a first selector switch at *A*. This switch would extend it to a second selector at *A*, which would extend it back over another trunk to a connector switch at *S*-2. This connector switch would complete the connection to line and telephone No. 2536. During such a conversation, therefore, two trunks would be occupied between the sub-station and the office through which it operates. This indicates that a sub-station is best adapted to a district where there is very little local telephonic intercourse, because every local connection occupies two trunks without any immediate benefit.

The sub-station is also especially adapted to a small isolated district where the expense of a constant local attendant would not be warranted, and, where it is, therefore, considered advisable to install the simplest apparatus obtainable, with arrangements for supervision from the main office to which the sub-station trunks are connected. Under almost any conceivable condition a sub-station will require more trunks than a branch office, for several reasons: first, all calls must be trunked; secondly, there is one group of outgoing and one group of incoming trunks for each 100 lines connected to the sub-station; thirdly, in order to provide thorough supervision from the main office, each outgoing trunk contains three wires instead of two.

It is, therefore, seen that in considering the advisability of installing a sub-station instead of a branch office, the increased expenditure for trunk installation and maintenance should be weighed against the saving in cost of supervision and attendance.

When the proposed office is to be a small one, and the trunks to it are to be secured by converting the line cable at present entering the new office district into a trunk cable, there is often no immediate advantage in economizing in the number of trunks. To such conditions a sub-station is well suited even if the trunks are long and consequently expensive. It would appear, however, that in the present state of the art such an auxiliary to a "main" office would rarely be warranted if it contained over 500 lines.

A sub-station may often be used to much better advantage as an auxiliary of a branch office; that is, a branch may be installed at the center of a comparatively large district so that all trunks going out from or coming into the district will terminate at the centrally located branch office, then shorter and more numerous trunks may be run from this office to sub-stations located about it. As an illustration of this plan please refer to Fig. 19 in which *A* represents an office of 5000 lines, *B* a branch office of 1500 lines, *S*-1 a sub-station of 100 lines, and *S*-2 another substation of 300 lines auxiliary to the branch office. Calls would be handled as follows: suppose, for example that a subscriber No. 8712 connected to sub-station *S*-2 called telephone No. 2134 connected to office *A*. As No. 8712 operated his calling device his line switch at *S*-2 would instantly operate and connect his telephone over an idle trunk to a first selector switch in branch office *B*. This first selector would be operated as the subscriber's calling device transmitted the first digit (2) of the number being called, and would extend the connection of the calling telephone over a trunk to a second selector switch at *A* office. The second digit (1) transmitted from the calling telephone would operate this second selector and extend the connection to a connector switch also located at *A*. This connector switch would be operated by the last two digits (3 and 4) of the number called, and would complete the connection to the line and telephone No. 2134. It might be of interest to note in passing that the current for the transmitter of the calling subscriber would be furnished from the battery located at *B* and the current to the called subscriber's transmitter from the battery located at *A*. If the call should proceed in the reverse direction, that is, if No. 2134 connected to *A* should call No. 8712 connected to *S*-2, then the operation of a line switch and a first selector switch at *A* would extend the connection over a trunk to a second selector at *B* which would in turn extend

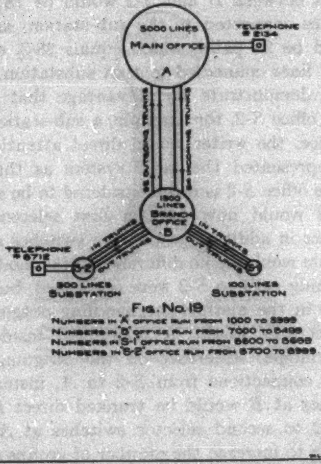

5000 LINES
MAIN OFFICE
A
TELEPHONE # 2134
25 OUTGOING TRUNKS
25 INCOMING TRUNKS
1500 LINES
BRANCH OFFICE
B
IN TRUNKS
OUT TRUNKS
IN TRUNKS
OUT TRUNKS
TELEPHONE # 8712
S-2
S-1
300 LINES SUBSTATION
100 LINES SUBSTATION

FIG. NO. 19

NUMBERS IN "A" OFFICE RUN FROM 1000 TO 5999
NUMBERS IN "B" OFFICE RUN FROM 7000 TO 8499
NUMBERS IN "S-1" OFFICE RUN FROM 8600 TO 8699
NUMBERS IN "S-2" OFFICE RUN FROM 8700 TO 8999

it to a connector switch at *S*-2. This connector switch would complete the connection to line and telephone No. 8712.

Supposing the number of calls made per line per day in this 6900 line system to be 16, and the number of busy hour calls to be one-eighth of the total, and that the "community-of-interest" can in all cases be taken care of by the factor 0.75, then the number of incoming trunks necessary to *B* from *A* would be 94, and the outgoing trunks to *A* from *B* would be 95, a total of 189. This number is 9.9% of the total of 1900 lines in the branch office district. The number of pairs of wires necessary for incoming and outgoing trunks, supervision, furnishing ringing current, charging substation battery and all other purposes between *B* and *S*-2 would be 78; that is, 26% of the 300 lines connected to the sub-station, and between *B* and *S*-1 would be 28 pairs, which equals 28% of the number of subscribers' lines connected to that substation.

In order to demonstrate the advantage that there may be in making the office *S*-2, for example, a sub-station instead of a "branch" office, the writer would direct attention to Fig. 20, in which is represented the same system as that in Fig. 19, except that the office *S*-2 is now considered to be a branch office of "B". *S*-2 would now contain first selector and second selector switches in addition to the line switches and connector switches. There would be no difference in the mode of operation so far as incoming calls to *S*-2 were concerned, but there would be a difference in the method for handling outgoing calls; also all local connections would be completed inside of the *S*-2 office. The principal difference in the outgoing connections would be that connections from *S*-2 to *A*, instead of passing through switches at *B* would be trunked direct from the first selectors at *S*-2 to second selector switches at *A*. The effect of this would be to increase the number of groups of trunks and consequently the number of circuits necessary between *A* and the *B* districts, so that with the particular case illustrated in Fig. 20 the total number of trunks between *A* and *B* would be increased by 15, while a reduction of only 12 circuits would be secured between *B* and *S*-2. It is, therefore, readily seen that if the distance from *A* to *B* is equal to, or greater than, the distance from *B* to *S*-2, that the branch office scheme in Fig. 20 would require more trunk mileage than the sub-station scheme in Fig. 19. The writer believes that this fairly illustrates the advantage that there may often be in using the sub-station as an auxiliary of a branch office.

As an illustration of how trunking of calls is done in a larger automatic system, Fig. 21 shows a rough skeleton of a 50,000-line system. This contains 5 main offices, *A*, *B*, *C*, *D*, and *E*, of which *A* has 8 branch offices and the other main offices each have 5 branch offices. Since this system has an ultimate capacity of 100,000 lines, all numbers would have five figures, but, as is customary, in place of the first figure a letter is used, which not only makes the number easier for the subscriber to remember, but also designates the office to which the number belongs. It is supposed that the main office *A* contains equipment for 2000 lines, the numbers of which run from 1000 to 2999; and that each of its branches contains equipment for 1000 lines, the numbers in *A*-3 running from 3000–3999, in *A*-4 running from 4000 to 4999, etc. Each of the other main offices is also supposed to contain equipment for 2000 lines, the numbers of which run from 1000 to 2999 in each. Of course, there is a letter prefix to each number corresponding to the office to which the number belongs. Each branch of the offices *B*, *C*, *D* and *E*

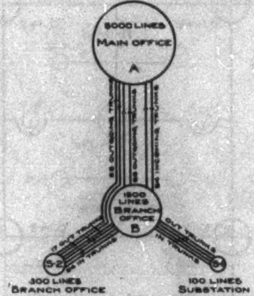
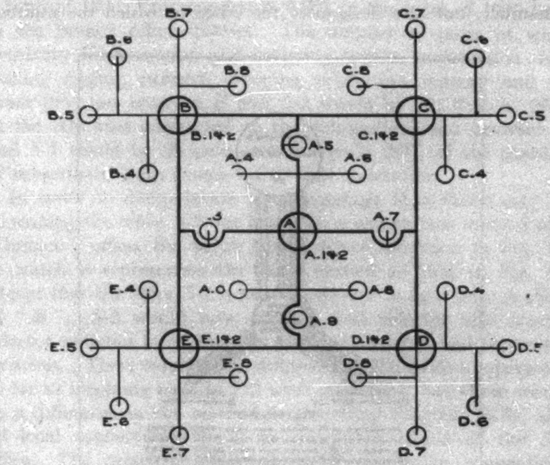

5000 LINES
MAIN OFFICE
A
58 OUTGOING TRUNKS
58 OUTGOING TRUNKS
54 INCOMING TRUNKS
1900 LINES
BRANCH OFFICE
B
17 OUT TRUNKS
24 IN TRUNKS
OUT TRUNKS
IN TRUNKS
S-2
S-1
300 LINES
BRANCH OFFICE
100 LINES
SUBSTATION

FIG. No. 20

NUMBERS IN "A" OFFICE RUN FROM 1000 TO 5999
NUMBERS IN "B" OFFICE RUN FROM 7000 TO 8499
NUMBERS IN "S-1" OFFICE RUN FROM 8600 TO 8699
NUMBERS IN "S-2" OFFICE RUN FROM 8700 TO 8993

is supposed to contain 1000 lines. The numbers in *B*-4, for example, run from 4000 to 4999, those in *B*-5 run from 5000 to 5999, etc.

Connections in the system would be handled as follows:

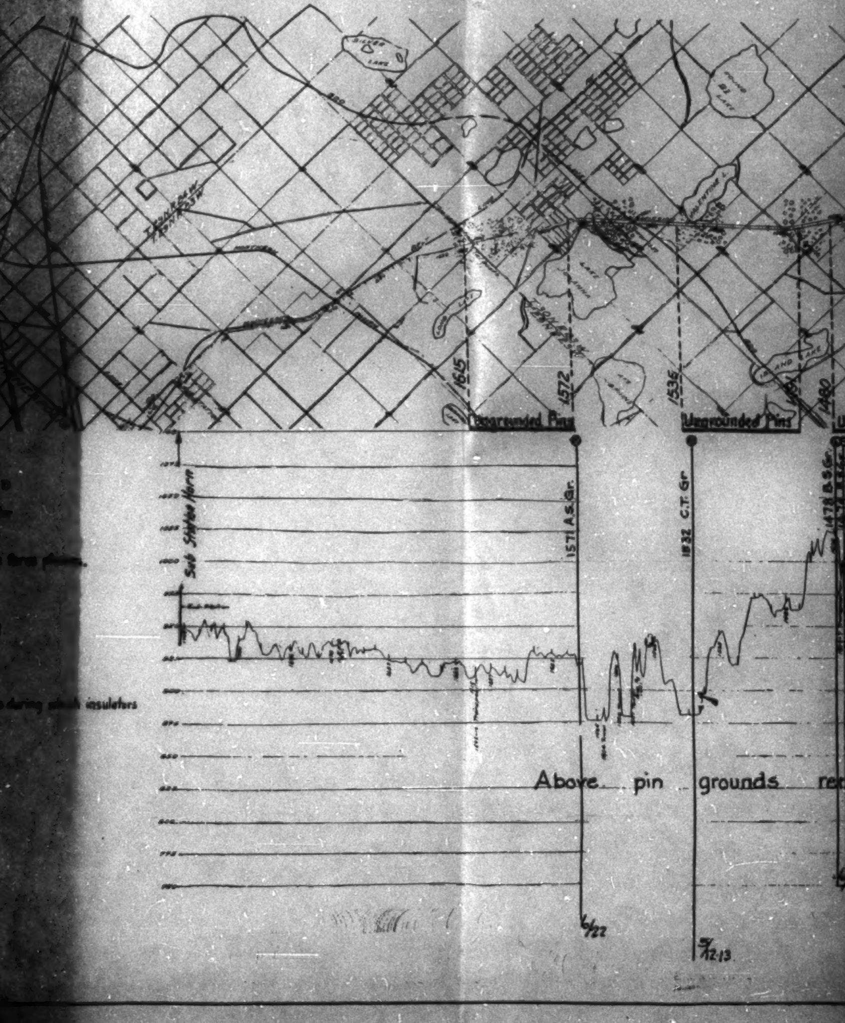

B.7
B.6
B.8
B.5
B
B.1&2
B.4
C.7
C.6
C.8
C
C.5
C.1&2
C.4
A.5
A.4
A.6
.3
A
A.7
A.1&2
E.4
A.0
A.8
D.4
A.9
E
E.1&2
D.1&2
D
E.5
D.5
E.8
D.8
E.6
D.6
E.7
D.7

SKELETON OF DIVIDED 50,000 LINE AUTOMATIC SYSTEM.
FIG. NO. 21

suppose a subscriber *E*-7234 connected to branch office *E*-7 called *A*-5124 connected to the branch office *A*-5. The first movement of the subscriber's calling device would operate his line switch and connect his line to an idle first selector in his own exchange, *E*-7; then when the calling device sent in a num-

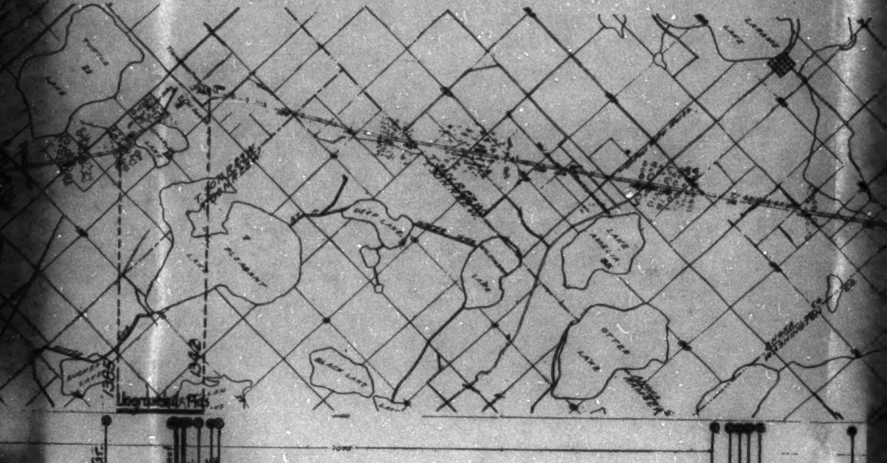
three phases.

during which insulators



Silver Lake
Round Lake
Valentine L.
Island Lake
Lake Johanna
Long Lake
T29N R24W
T30N R23W
1615
1572
1536
1480
Ungrounded Pins
Ungrounded Pins
Sub Station Harr
1571 A.S. Gr.
1532 C.T. Gr
1478 B.S. Gr.
Above pin grounds re
6/22
5/12.13

# ST. CROIX


Turtle Lake
Pleasant Lake
Deep Lake
Lake Amelia
Otter Lake
Black Lake
Sucker Lake
Lake
1385
1342
1387 C.S.Gr.
1150 B.S.Gr.
C.T.
8/18

Aug. 1, 1907.

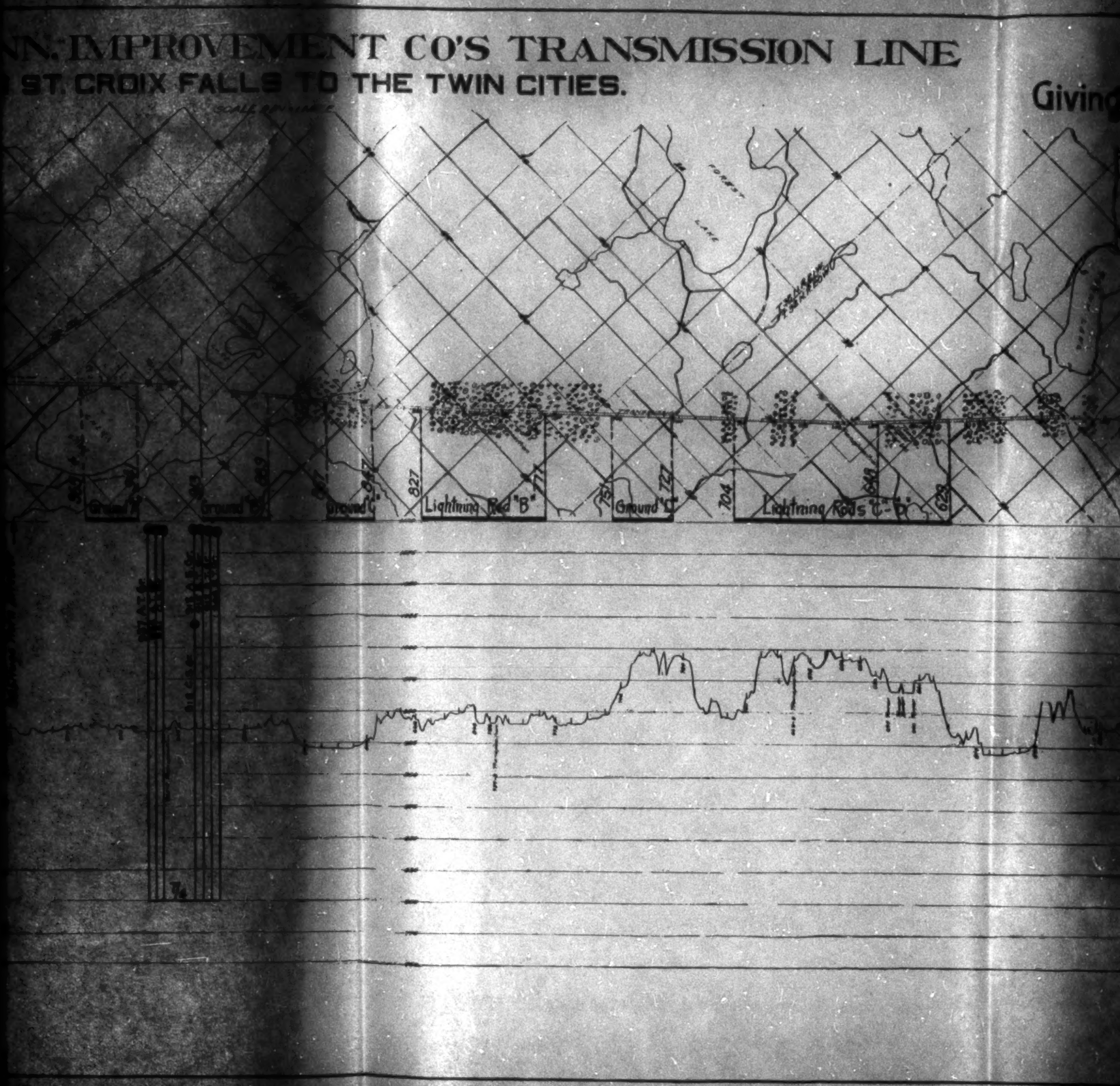
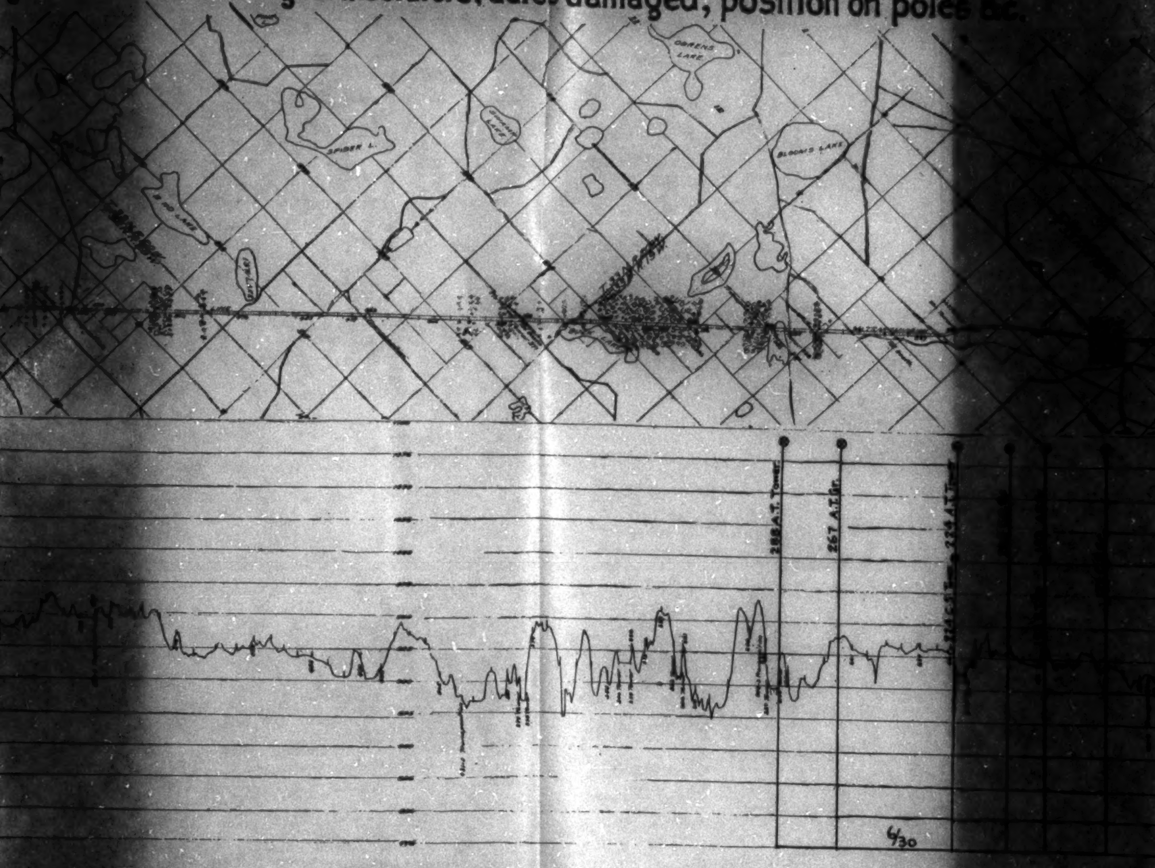

NN. IMPROVEMENT CO'S TRANSMISSION LINE
ST. CROIX FALLS TO THE TWIN CITIES.
Giving
FOREST LAKE
Ground "A"
Ground "B"
Ground "C"
827
Lightning Rod "B"
771
751
Ground "D"
727
704
Lightning Rods "C"-"D"
648
629

Fig. 8.—Plan and profile of line showing location of damaged insulators.

# Plan and Profile of Line

# g locations of damaged insulators, dates damaged, position on poles &c.



SPIDER L.
OBRENS LAKE
BLOOM'S LAKE
268 A.T. Tower
267 A.T.Tr.

6/30

ber of impulses corresponding to the No. *A*, his first selector would be operated and would pick out an idle trunk to a second selector in exchange *A*. The second set of impulses corresponding to the figure 5 sent in by the calling device would operate the second selector at *A* and extend the connection over an idle trunk to a third selector in the office *A*-5. The next set of impulses corresponding to the 1 of the desired number would operate a third selector at *A*-5, which would extend the connection to a connector switch in the proper " 100 group " at *A*-5. This connector would be operated by the impulses corresponding to the last two digits of the desired number and would complete the connection to line and telephone *A*-5124.

It may be noted that on this call the connection to *A*-5 passes through the main exchange *A*. This would be true of every call incoming into the *A* district; that is, all trunks incoming into the district would terminate in second selectors in the *A* office. These second selectors would extend each incoming connection to a third selector located at the *A* main office, or at the branch corresponding to the thousands digit of the particular number being called. This concentration of the incoming circuits simplifies the trunking arrangement and also reduces considerably the number of trunks entering the district, because the number of groups of incoming trunks would be nine times as great if each of the nine offices received its calls, coming from outside the district, direct instead of having them come through the main distributing office *A*. It should be noted on the other hand that the outgoing call from *E*-7 does not operate any switch at its main office *E*. It would probably be preferable, however, to have the trunk pass through the cross connecting frame at *E*. In a similar manner all outgoing trunks from each of the branch offices of *E* district could be terminated on the distributing frame at *E*, and there be cross-connected to what might be called a " through trunk cable " to each of the other main offices. If a subscriber connected to any office in the *A* district should call a number connected to an office in *E* district the incoming trunk to *E* district would terminate in a second selector switch at main office *E*, and would be passed on by it to the desired branch office or thousand group. In the skeleton diagram no trunk cables are shown interconnecting the branch offices of a district; for instance, no interconnection is shown between E-6 and E-7. If desired such trunks could be put in, or the outgoing trunks from all the branch offices of *E* may, as already stated, be run to the main central office and there be cross connected on a distributing frame. This would in many cases be the most economical arrangement, because with division carried to the extent that it is in this diagram the number of trunks required between *E*-6 and *E*-7 would be comparatively small. A call from a subscriber at *E*-7 to a subscriber connected to *E*-6 would operate a line switch, first selector and second selector at *E*-7 and a third selector and connector at *E*-6 so that it is not necessary that the connection should pass through the main office *E*.

If a manual system should be divided up in the manner shown in Fig. 21, supposing for the moment that such a division would be practical with equipment of that type, then the branch office *E*-7, for instance, would have 32 different groups of outgoing trunks; that is, one group for each of the other offices in the system, and would have the same number of groups of incoming trunks. With the automatic branch office arrangement, *E*-7 has but 10 groups of outgoing trunks; that is, one group to each of the other district main offices and one group to each other " thousand section " in use in its own *E* district. *E*-7 would have but 5 groups of incoming trunks; that is, one group from each of the other offices in the *E* district. It is, seen, therefore, that by using the main offices at centers of comparatively large districts and then surrounding each main office with smaller branches, all subscribers lines may be made very short and the use of the " through " trunks between the main offices for interconnecting districts makes the trunking system comparatively simple.

It is probably unnecessary to add that in planning such a system as is represented by Fig. 21, a careful engineering study should be made for each branch office to determine whether the trunk mileage required would make a " branch " office or a " sub-station " the most economical arrangement.

One of the peculiarities of the telephone business, especially when there is competition, is that an operating company is compelled to take on the new business offered. It must keep up with its rival or drop out of the race. A user of electric light doesn't care how many other customers are connected to the same plant that he is, but a telephone user is, of course, very much attracted by the larger of two lists of subscribers. Unfortunately a one-office plant is somewhat like a water or gas plant, in that new customers cannot be constantly added by simply connecting their service pipes to the mains originally installed. Some day a point is reached when the mains are supplying all the flow of which they are capable and it is necessary to go back to headquarters, dig up the streets anew, and put in more mains or larger ones. So in a one-office telephone system, if the growth is more rapid than anticipated, as it often is, or if the growth of the city takes place in an unexpected direction, as it frequently does, it becomes necessary to remodel the cable and wire plant to suit the new distribution of business.

A one-office telephone plant sometimes must be almost entirely rebuilt within a few years of its installation in order to adapt it to a shifting of population, or to make it adequate for the customers unexpectedly demanding service.

With a multi-office automatic system this need not be done. If an unexpected demand for telephones develops in a certain section of the city, it is not necessary to put in more conduits and cables or to replace present cables with larger ones to take care of the demand, but the situation is readily and practically met by putting in a substation or a branch office in the congested district. The present line cables running to the district may be used as trunk cables to the new office. Thus the traffic carrying capacity of the cable and conduit plant reaching any district may be greatly multiplied without any additional expenditure for cable or duct. Consequently, one of the most attractive features of an automatic multi-office system is that it affords a stable value to the investment in wire, cable, and conduit.

## DISCUSSION ON "A STUDY OF MULTIOFFICE AUTOMATIC SWITCHBOARD TELEPHONE SYSTEMS." ATLANTIC CITY, N. J., JUNE 29, 1908.

**A. B. Smith:** For a number of years it has been my hope that the automatic would be able to solve the telephone problem for large cities; that it would bring the rental a little lower for the benefit of the many who need the telephone but cannot now afford it, and that it would afford relief from the party line. That this can only be done by subdivision into small offices with short subscriber lines is acknowledged, but the apparently insurmountable obstacles of trunk lines and office expenses have stood squarely in the way. However, it may now safely be said that the automatic has arrived at that point of development where its claims merit serious consideration.

With regard to the claimed flexibility of the system in being able to use subscribers' lines for trunks, I ask if it would not seriously interfere with the practice of making trunk cables of lower resistance and electrostatic capacity than subscribers' cables? It would necessitate making the whole installation of cables good enough for trunks, which would be very expensive.

In a continuously growing city the telephones increase in number in two ways—increase of density and increase of territory. If merely the telephone density increased, and the transmission equivalents had been properly cared for, any district might be converted into a branch office and old subscriber lines used for trunk lines with no loss. But all around the edge of the city the telephone exchange is expanding and the length of lines increasing, so that to continue indefinitely with the process would eventually make transmission very poor. In this respect the automatic offers no additional advantages except as it makes profitable a smaller branch office.

In a multioffice automatic exchange the trunk repeater is used to relay the calls and permit each subscriber to draw talking current from the nearest battery. This introduces added complications into the selecting mechanism, but as far as talking is concerned a little comparison will show the conditions. In the common battery manual trunk circuit there are two repeating coils between the two subscribers, one in the cord circuit at the *A* board, the other in the trunk circuit at the *B* board.

No repeating coils are used in the automatic, their place being taken by the condenser-retardation coil combination so common in independent cord circuits. From a test which I recently made, the repeating coil is considerably less efficient as a transformer of speech than the condenser-retardation coil combination. Hence the insertion of the trunk repeater into the line will still leave the automatic with an excellent transmission circuit.

Where there are a number of groups of trunks from one office district to another, as from $E$ to $A$, Fig. 21, it seems that there would be considerable advantage in making all the trunks more or less accessible to all the offices in that district. I ask Mr. Campbell if this can be done? If so, the number of trunks can be reduced and still have the same busy hour capacity as a whole.

For the benefit of many who may not now take kindly to the idea of an all automatic plant, I ask if the line switch or some other device can be used on manual boards to trunk small groups of subscribers to the office? My idea would be to place such a switch at the center of the subscriber group with as many trunks to central as necessary. When any subscriber in the group takes the receiver from the hook, he is automatically trunked to the manual board and answered by the operator just as if he were on an ordinary line. It would enable the giving of individual line service with as few wires as would be required for party lines. Has this been suggested or worked out, and is it considered practical?

**John Wicks:** This paper offers encouragement to those connected with the development of automatic telephone service. Few engineers have yet given the matter sufficient thought or study to enable them to see its possibilities. The fact that telephonic connections are made automatically has been viewed as a curiosity. That the public in large communities has made use of it for years, even in preference to the best manual service offered by competing companies, is still looked upon as incredulous. Many have wondered at its rapid general adoption, but few have stopped to investigate the reason of its growth. It is therefore interesting and gratifying to learn that it has developed along a line which makes it possible to decrease the great economic waste, which in the form of idle lines is to be found in the old-style telephone systems.

Automatic telephone service has been tried sufficiently to prove itself practical. We know that the telephone-using public likes it. We know also that there are no mechanical or electrical difficulties in the art which cannot be overcome. To compete with manually operated telephone systems, therefore, it has only to prove itself economically more efficient than its rival.

In manually operated exchanges, party lines were long ago resorted to as a part solution of the problem involving the reduction of the percentage of idle lines. So important has this branch of the service been considered that a prominent telephone engineer stated only a few years ago that a grave objection to the automatic equipment was that it had no party lines. The manufacturers of automatic switchboards have since then successfully solved the party-line problem, but it is hoped that the introduction of multioffice automatic switchboards will eventually do away with a large part of party-line service without putting the rental above the reach of present party-line subscribers.

The principal reason for the moderate price of party-line service is the saving effected in line construction by using one line for several telephones. A similar reduction in line investment is obtained by the use of a large number of small offices interconnected by trunk lines. It has the advantage of offering individual lines to patrons who can now afford only party lines.

A plan has been proposed and is now about to be tested in an eastern city which, if successful, will enable a telephone company to offer a still cheaper direct line service. This new service might be termed "limited trunk" service, because the scheme is to limit the number of trunks to the main office from the district station to which the limited trunk subscribers are connected. For example, if 100 telephones, instead of being connected to the main central office by 30 or 40 party lines, should be connected individually to a 100-line switch unit in a district station, this district station may then be connected to the main central office by a number of trunks less than that necessary for furnishing each telephone a trunk line whenever demanded. For instance, the number of incoming and the number of outgoing trunks connected to the line switch unit might each be limited to five, thus making a total of 10 trunks instead of 30 or 40 party lines. It can readily be arranged so that any party attempting to call when all of the trunks outgoing from the district station are busy, will receive either the ordinary busy signal, or preferably a peculiar signal, which will inform him that all trunks are occupied for the moment and that he should call again in a few minutes. It often happens that one subscriber keeps a party line busy for an unnecessarily long period to the inconvenience of others on the line, but it would be impossible for any one or two inconsiderate subscribers to occupy all of the trunks from a district station. Another marked virtue of this limited trunk service is that communication would be absolutely private, thus eliminating one of the most objectionable features of party-line service.

There may be questions raised as to the advisability of having a small sub-station with its apparently complex line switches and connectors without an attendant, but experience has proved that even the operation of large switchboards contained in one room is done to a large extent through supervising signals. If a line becomes grounded or open, or if something goes wrong with the switching mechanism, attention is called to the matter by means of a signal, which may as readily be made to appear in another office miles away. Should the trouble be in the subscriber's line or instrument, no other part of the sub-station is affected, whereas a trouble in a party line will frequently throw all the instruments connected to that line out of service. Any part of the switching mechanism going wrong will affect only the trunk connected to that particular switch, and that can be made "busy" from the main exchange until it is convenient to repair it.

Apparently, rural or extremely isolated subscribers would still have to be furnished party-line service, but it would appear that multioffice and limited trunk multioffice service might be used both to the advantage of the telephone company and its patrons to dispense with the majority of the party lines.

The possibilities of limited trunk service will be still further enchanced, especially for residence districts, when the manufacturers of automatic equipment put apparatus upon the market that will make two-way trunks practical. It will then be unnecessary to have one group of trunks for handling outgoing calls and another group for incoming calls, but each trunk will be available for a call going in either direction. It is a well-known fact that the maximum flow of traffic from the residence districts to the business district of a city does not occur at the same time as the maximum flow in the opposite direction. Consequently, if the trunks could be used in either direction a less number would be needed. Two-way trunk equipment is possible, in fact has been tried experimentally a number of times during recent years. It is my belief that it will eventually be made a commercial success.

**E. A. Mellinger:** Practically the only argument which can at the present day be consistently advanced against the automatic system is the first cost of the apparatus, which, as indicated in Fig. 5, is considerably greater for a single automatic exchange than for a single manual exchange, except in cases of very large switchboards. In some instances this is a factor of more immediate importance in deciding what equipment shall be installed than is the comparative cost of operation and maintenance.

Mr. Campbell demonstrates the entire practicability of subdividing the automatic exchange to an extent not economically possible in manually operated switchboards. It is probable that, even with a comparatively limited subdivision, from 50% to 75% of the cable required for a single exchange can be eliminated. In comparison with the economy thus effected the additional first cost of the automatic switchboard is of small importance.

Since the cost of maintenance and operation of an automatic exchange is almost inappreciably increased by subdividing it into branches of 1000 lines or more, and since, obviously, the service is unaffected by such subdivision, the only items to be considered are the slightly increased cost of apparatus and buildings. With reference to the cost of apparatus, there can be no doubt but that there will be some increase with subdivision, owing principally to the present necessity for separate battery-supplying units; but in many instances there would be an actual saving in the cost of building, on account of the comparatively low value of building locations required for the branch offices. The central exchange is usually located of necessity in the heart of the business district where land values are at the highest, and any reduction in space required here would much more than compensate for a corresponding increase in branch office space. It is probable also that less expensive building construction could be employed in branch offices than in central exchanges.

For the small sub-station serving an outlying district it is customary to rent space in some office or store building, or to erect a small building for housing the apparatus; but in an exclusive residence district it is sometimes difficult to obtain space in a suitable location. In at least one instance this difficulty has been successfully met by placing the sub-station under ground in a moisture-proof cement vault, similar to those used for housing batteries in railway signal work. The most logical location for a sub-station is usually at the manhole where the cable distribution for the district begins, and since no serious objection has been encountered in the installation and operation of the underground sub-station, there appears to be no reason why the manhole itself cannot be constructed to accommodate the switching apparatus, thus eliminating the necessity for building space.

The vault, or monolith as it is called, to which reference is made, was constructed complete in one piece before being lowered into place. It is elliptical, its dimensions being 4 ft. 10 in. by 7 ft. 8 in. by 6 ft. high, and accommodates a 100-line unit together with protector and distributing rack, batteries, etc. The average manhole is almost as large.

Carefully kept thermometer and barometer records indicate a practically constant temperature of 70 degrees fahr. and an almost complete absence of moisture, except as the presence of the troubleman or others in the vault for half an hour or more changes the normal atmospheric conditions. After such visits the vault is quickly dried by lighting an incandescent lamp for a short time. A small ventilating fan would doubtless prevent any moisture precipitation while the vault is open.

Every city has one or more telephone districts so far removed from the telephonic center that the installation of the sub-station is an economic necessity, particularly since the telephones in these districts usually yield smaller rentals than those centrally located. Such districts are being satisfactorily served by trunking stations of from one to five hundred lines in a number of automatic exchanges in various cities, but the limit of practical distribution appears by no means to have been reached. It is more than probable that in the not very distant future every large office or apartment building will have its sub-station trunking to the nearest branch exchange, even though the distance be only a few blocks, and that these trunking stations will in most cases be a part of the underground system.

From the underground sub-station to the underground branch exchange is not a long step, and although the branch office is usually of such size as to require the constant presence of one or more attendants, the necessity for artificial light and ventilation is hardly to be counted as a serious objection. The economy which could be effected in the business center of large cities by such an arrangement is apparent.

**Morgan Brooks:** Mr. Campbell's paper speaks of the economic waste represented by 90% of the wire plant being idle even in the busiest hours. Imagine, if you please, a much smaller waste, such as 50%, and it is evident that the busy signal would be received from half the calls. Good service demands a minimum of busy signals, and necessitates economic waste. The author has shown that the quickness of disconnection characteristic of the automatic system helps the service, especially with trunk lines, although it evidently increases the percentage of non-use. It is only in private branch exchanges that good service may be coupled with a reasonably large load-factor of subscribers' lines.

**L. E. Hurtz:** A word or two about these sub-stations. Mr. Campbell speaks from the manufacturer's point of view; I speak from the operator's point of view. A very large advantage in the use of these sub-stations over the ordinary type of equipment is the fact that the exchange can be divided into units as small as one hundred lines. When considering the cable distribution of a telephone plant, the reasons that make it necessary to subdivide very large districts into several smaller ones are well understood. The question then arises as to the proper time to stop sub-dividing. In manual practice, on account of the cost of buildings and equipment and in order that satisfactory and economical service can be given, these branch exchanges vary in size from 1,000 to 10,000 lines, according to the density of the telephone development in that vicinity. With the use of low-priced buildings and low labor costs it is practical with these automatic switching units to reduce the size of these branch exchanges to one or several hundred lines, which increases the savings due to sub-division to a corresponding extent.

In our experience of a year and a half, during which time we have had two sub-stations in operation, we find we can give high grade service with but little additional labor. It is an easy matter to realize what vast savings can be made in the cable plant by use of this system. The saving in investment and maintenance cost and interest cost must be equated against the additional labor; if the additional labor item is low enough there is a big saving. This system is being tried in several places. Our experience with it leads me to believe that it is thoroughly practical and will work out as well as indicated by Mr. Campbell.

I am convinced that one of the greatest developments made in telephony in recent years is the production of this switch unit. It is possible now to put in sub-stations as small as one hundred lines, locating them at isolated points, and at the same time not increase the operative and maintenance expenses to any considerable extent.

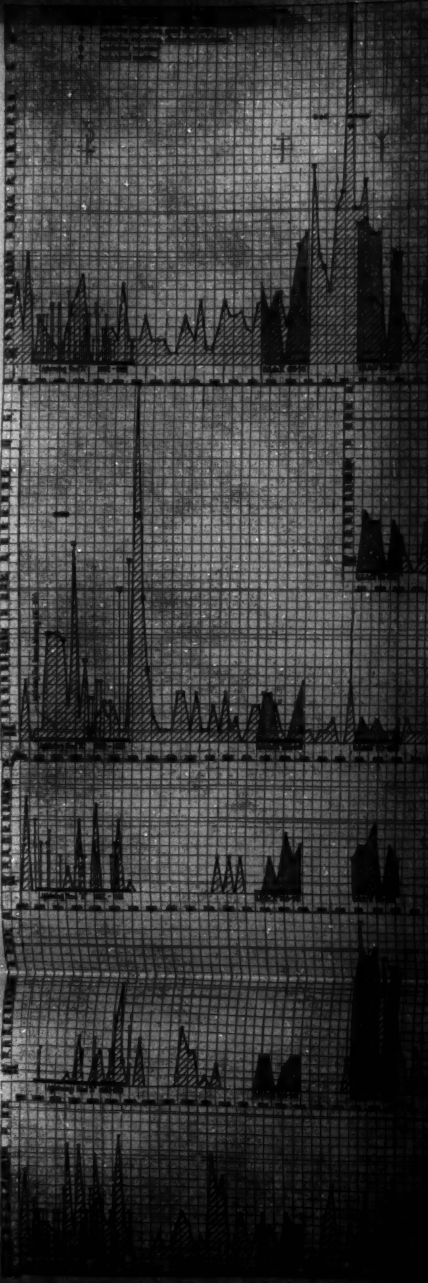
**Samuel G. McMeen** (by letter): The economic waste of which Mr. Campbell treats has been recognized for many years, and efforts have been made to reduce it in manually operated systems. In most of the cases the effort has been successful. The method of waste-reduction by automatic apparatus, as treated by Mr. Campbell, is the most important recent attack, and is one from which a very large amount of new knowledge may be expected to be drawn.

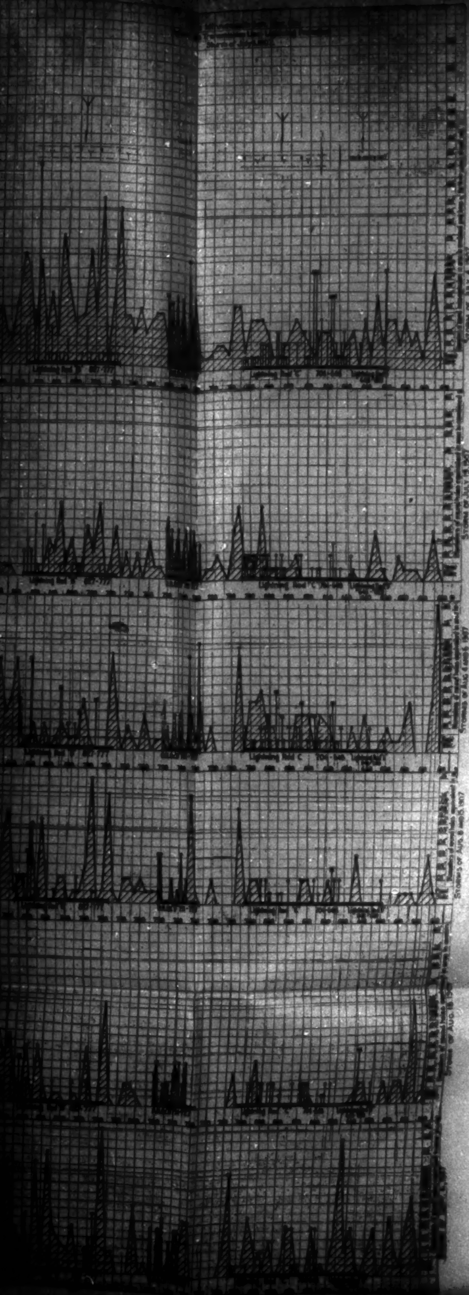
The broad idea of dividing a telephone exchange wire-plant into two general parts, and then using one part at a high efficiency and the other at a low, is not new. It has been proposed again and again, and has been developed for various forms of apparatus and various arrangements of wire-plant. The planetary system of operating manual equipment was such an effort, proposed eight or ten years ago by Mr. Angus S. Hibbard. In that system all calls needed to be trunked from a small local office, in which they were first received, to a central switching office, even though they might need to be trunked right back again to the small first office to find the sought lines.

The telephone requirements of the business area of every city are served very largely by private-branch exchanges, privately operated. About two-thirds of the traffic originating in them requires to be trunked to a main exchange operated by the telephone company. If these private exchanges were to trunk *all* their originated business, even at the cost of receiving again all local calls, such a plan would be a *manual* counterpart of the waste-saving system Mr. Campbell describes. As it is, the plan is a real counterpart so far as concerns the traffic for which, mainly, a private branch exchange exists, and the object is the same—to save wire-plant at a cost for apparatus and attendance.

A proof of the widespread wish to make such a wire-plant saving is to be seen in the long effort to produce a selective and secret party-line equipment. It is possible to-day to have and use such a party-line system, but at best the privileges of the line are divided among the subscribers upon it. None has the same good condition as the subscriber on a single pair of wires, all his own. In either manual or automatic practice, the amount of central office equipment is controlled by the traffic, which party-lines do not reduce, unless by discouragement caused by poorer service. All that a party-line can do, at best, is to save something of the annual cost of its line, and unless this line be longer than a certain minimum, nothing at all is gained, and always something in quality of service is lost.

A condition not brought out by Mr. Campbell may well be considered as next in importance to the savings he treats of. I refer to the saving possible in the *character* of lines, as distinguished from their *extent*. The subdivision of the plant, so as to have many and short subscribers' lines, connecting over long and few trunk lines, enables the kind of circuits of both sets of lines to be reviewed with great gain. What I mean is this: the facts which govern the choice of circuit elements for subscribers' lines are much dependent upon distance. The conductivity of the sub-




Storm of July 4, 1907
Lightning Rod C
Storm of July 19, 1907
Storms of Aug 4 and 6 1907
Storms of Aug. 8 and 15, 1907
Storms of Aug. 18 1907

scriber's loop governs the amount of current deliverable to his transmitter from a fixed-voltage central source. The capacity of the loop governs both transmitting and receiving. For a set standard of either, it is possible to distribute the lines of a subscriber's district, if that district be small, through cables of much smaller wires squeezed into a much smaller bundle and covered by a much smaller lead sheath, than if the district be a large one and the average lines be long. As the transmitter current problem is a direct-current distributing one, the analogy is that of large and small districts in direct-current power distribution, with the further advantages that the telephone problem involves great numbers of circuits, in each of which a small saving can be made.

For example, most subscribers' lines in multioffice manual practice require cable circuits of No. 22 B. & S. gauge wires, having a mutual capacity of not over 0.06 mf. per mile and a resistance per mile of loop of about 190 ohms. Assume that a system satisfies working conditions with such cables when the longer lines of a district have a length of somewhat under two miles and a loop resistance of, say, 350 ohms. If it were recast so as to be served by more centres, with maximum lines in each of a half-mile, a cable formed of No. 28 B. & S. gauge wires, pressed so tightly together as to have a mutual capacity of 0.22 m.f. per mile, should give similar results. Equally, wires of other metals than copper may be used, with a gain in certainty of jointing and terminating, and the reduced sheath diameter is accompanied by a reduction in its thickness.

The foregoing presumes that each small district contains its own source of current, so that the calling and the called subscriber each receives transmitter current over the minimum length of line. Experience with operating conditions shows this to be a preferred arrangement, for reasons other than transmitter supply; and the increased efficiency of transmission in private branch exchanges having localized current sources for trunked connections emphasizes the point.

Mr. Campbell's observation of the shorter holding of the line in an automatic system seems to be generally noted. It is a psychological matter more likely to be discovered than predicted. The same is true of quicker answering and less waiting for answer after actual ringing has been done. These differences in the actual performance of the two systems need to be considered in any study involving comparisons. The longer time of *initial* holding of interoffice trunks seems also to be overbalanced by the speed of disconnection in the automatic apparatus, and to this must be added a consideration of the slowing down of disconnecting efficiency on the part of the manual *B* operator during the rush period.

No casual study of large city work fails to show the beginner the influence of sub-division of districts on the amount of trunking. The percentage of calls trunked out of the New York

Cortlandt Street subscribers' board in 1896 was 75; in 1902 it was 90 or more, and to-day, under accepted manual practice for such surroundings, it is 100; that is, it is not worth while to complete any call directly in a manual multiple of lines when so few as a tenth of them can be so completed. Mr. Campbell's point of trunking all calls in an automatic system is of equal force in view of that tendency in manual practice, and of the present trend of thought in partly automatic manual systems.

A feature on which more might have been said is the possible danger of excessive changing of subscribers' numbers. It must be admitted that anything which endangers a subscriber's privilege to keep the same telephone number through a term of years is a bad thing. In a one-office exchange that danger is least, and under ideal conditions may be nothing, for the main distributing frame in that one office enables the central office equipment to follow up his line, into whatever quarter of town he may move. But in a multioffice system, it is a penalty upon the subscriber that he must change his number when he moves from district to district. The more districts there are, the worse it is for him. But it is further a hardship that in cases of relief of congested regions, as suggested toward the close of the paper, a subscriber may awake to find his number changed overnight, through no fault of his own. Certain care in districting regions, and certain stubbornness in following the resulting plan, will prevent a large part of the changes required by future splitting of original sub-office districts. It is strongly to be recommended that this forecasting be done, for the number-changing evil is one in which party-line and sub-office systems are alike.

**W. Lee Campbell** (by letter): Professor Smith asks if it is possible to make all of the trunks from *E* office to *A* office in Fig. 21 accessible to all of the subscribers. It is possible, in fact, equipment of the necessary type has already been installed for trial and is operating satisfactorily.

He also asks if line switch sub-stations could not be used with manual telephones in connection with a manually operated central office. I would reply that they could be, and probably will be.

Concerning the plan for relieving a congested district by converting the line cable into a trunk cable, I wish to say that this would often improve transmission from the original telephones, because it would bring the battery closer to the transmitters drawing current from it.

This feature might even permit the district to be enlarged; that is, new patrons farther away might be added and their transmission be equal to that afforded the original subscribers, before the new local office was installed.

I think that in economically designed plants the conductors of the trunk cables are not made heavier than the lines, unless the distances are so great that heavier wire is necessary to keep the transmission up to standard. In other words, the subscribers in the district reached by such a cable would have to be served by heavier conductors if no branch office were installed in that district. I see no reason, therefore, why adding to the number of offices should increase the amount of large conductor cable used for trunks; it appears to me that it would tend to decrease the amount.

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# WIRELESS TELEPHONY

BY R. A. FESSENDEN

## Synopsis

A. Preface.

B. Brief history of the development of wireless signaling.

1. Introduction.
2. Period 1838–1897. Origin and development of old or damped wave-coherer method.
3. 1898. Return to first principles and foundation, on lines antithetical to old, of new or sustained oscillation-non-microphonic receiver method.

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During the course of this work, now extending over twelve years, since 1906, I have naturally incurred indebtedness on all hands. Amongst others to whom my thanks are due are: Professor Kintner for much valuable assistance in the experimental work; Mr. Brashear, for his kindness in making up a number of special pieces of optical and other apparatus for use in the work; Mr. H. W. Fisher, and to Professor Frost, for the loan of electrical apparatus. For the development of the high-frequency alternator, I have to thank Messrs. Steinmetz, Haskins, Alexanderson, Reist, Geisenhoner and Dempster, and Mr. Guy. For much valuable assistance in the construction of my transatlantic apparatus, I am obliged to Mr. Green. Especially am I indebted to the gentlemen who have acted as my assistants during the progress of the work, especially Mr. Stein and Mr. Mansbendel and Mr. Bennet, Mr. Davis, Mr. Hill, Mr. Kroeger, Mr. Boyle and Mr. Bryant, and to our shop superintendent, Mr. Williams.

In order to avoid repetition, patents covering inventions made and developed by the writer without assistance or coöperation are referred to by the patent number and date only. Where there has been coöperation on the part of an assistant the patent has been taken out and referred to under the joint names of the coöperators. All inventions made or developed by assistants are taken out and referred to by the assistant's name.

4. Fundamental differences between the old and new wireless schools.
5. Period 1898–1902.
    - (a) Development and perfecting of sustained oscillation-non-microphonic receiver method.
    - (b) Further development of damped wave-coherer method.

6. Period 1902–1908. General abandonment of old method and adoption of new method. Later developments.

C. Theory of wireless telephony.
D. History of development of wireless telephony.
E. Methods and apparatus.
F. Operation.
G. Possibilities.
H. How wireless development has been prevented by governmental action.
I. Considerations.
K. Appendix.

## A. PREFACE

The discussion of the theory, practical operation, and possibilities of wireless telephony is facilitated by first briefly considering the history of the development of wireless signaling generally.

## B. BRIEF HISTORY OF THE DEVELOPMENT OF WIRELESS SIGNALING

1. *Introduction.* In preparing this note it has been considered best, for the sake of accuracy, to refer to published results, such as scientific articles or theses or patent specifications. For the sake of brevity, references to work done in repetition of previously published work has as a rule been omitted. So far as possible, the expression of personal opinion has been avoided in this section of the paper, the object being to gather together in concise form the facts known in regard to the development of the art. With the exception of Munk's original paper, which could not be obtained, all references have been verified by consulting the original publications, a work of some labor, and if any omissions or mistakes have been made data for their correction will be much appreciated.

2. *Period* 1838–1897. *Origin and Development of Old or Damped Wave-coherer Method.* Joseph Henry, to whose work

the development of wire telegraphy owes so much, was the first (1838-1842) to produce high frequency electrical oscillations, and to point out and experimentally demonstrate the fact that the discharge of a condenser is under certain conditions oscillatory, or, as he puts it, consists "of a principal discharge in one direction and then several reflex actions backward and forward, each more feeble than the preceding until equilibrium is attained ".[1]

This view was also later adopted by Helmholz[2] but the mathematical demonstration of the fact was first given by Lord Kelvin in his paper on "Transient Electric Currents ".[3]

In 1870 Van Bezold discovered and experimentally demonstrated the fact that the advancing and reflected oscillations produced in conductors by a condenser discharge gave rise to interference phenomena.[4]

Professors Elihu Thomson and E. J. Houston in 1876 made a number of experiments and observations on high frequency oscillatory discharges.[5]

In 1883 Professor Fitzgerald suggested at a British Association meeting[6] that electromagnetic waves could be generated by the discharge of a condenser, but the suggestion was not followed up, possibly because no means was known for detecting the waves.

Hertz[7] discovered a method of detecting such waves by means of a minute spark-gap and before March 30, 1888, had concluded his remarkable series of researches in which for the first time electromagnetic waves were actually produced by a spark-gap and radiating conductor and received and detected at a distance by a tuned receiving circuit.

Hertz changed the frequency of his radiated waves by altering the inductance or capacity of his radiating conductor or antenna, and reflected and focused the electromagnetic waves, thus demonstrating the correctness of Maxwell's electromagnetic theory of light.

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1. Scientific Writings of Joseph Henry, Smithsonian Institution.
2. Helmholz "Erhaltung der Kraft", Berlin, 1847.
3. Kelvin, *Philosophical Magazine*, June, 1853.
4. Van Bezold, *Poggendorff's Annalen*, 140, p. 541.
5. *Journal Franklin Institute*, April 1876.
6. Fitzgerald "On a method of producing Electromagnetic Disturbances of comparatively short wave lengths". *Report of British Association*, 1883.
7. Hertz "Electric Waves".

Lodge later in the same year read a paper on the "Protection of Buildings from Lightning"[1], before the Society of Arts, in which he described a number of interesting experiments on oscillatory discharges.

Great interest was excited by the experiments of Hertz, primarily on account of their immense scientific importance. It was not long, however, before several eminent scientists perceived that the property possessed by the Hertz waves of passing through fog and material obstacles made them particularly suitable for use for electric signaling.

Professor Elihu Thomson in a lecture delivered at Lynn, Mass., on "Alternating Currents and Electric Waves", in 1889, suggested this use.

Sir William Crookes in the *Fortnightly Review* for February, 1892, discussed the matter in some detail. I quote his statement in full as it shows what a clear conception he had of the possibilities and obstacles to be overcome:

> Here is unfolded to us a new and astonishing world, one which it is hard to conceive should contain no possibilities of transmitting and receiving intelligence.
>
> Rays of light will not pierce through a wall, nor, as we know only too well, through a London fog. But the electrical vibrations of a yard or more in wave length of which I have spoken will easily pierce such medium, which to them will be transparent. Here, then, is revealed the bewildering possibility of telegraphy without wires, posts, cables, or any of our present costly appliances. Granted a few reasonable postulates, the whole thing comes well within the realms of possible fulfilment. At the present time experimentalists are able to generate electrical waves of any desired wave-length from a few feet upwards, and to keep up a succession of such waves radiating into space in all directions. It is possible, too, with some of these rays, if not with all, to refract them through suitably shaped bodies acting as lenses, and so direct a sheaf of rays in any given direction; enormous lens-shaped masses of pitch and similar bodies have been used for this purpose. Also an experimentalist at a distance can receive some, if not all, of these rays on a properly constituted instrument, and by concerted signals messages in the Morse code can thus pass from one operator to another What, therefore, remains to be discovered is—firstly, simpler and more certain means of generating electrical rays of any desired wave-length, from the shortest, say of a few feet in length, which will easily pass through buildings and fogs, to those long waves whose lengths are measured by tens, hundreds, and thousands of miles; secondly, more delicate receivers, which will respond to wave-lengths between certain defined limits and be silent to all others; thirdly, means of darting the sheaf of rays in any desired direction, whether by lenses or reflectors, by the help of which the sensitiveness of the receiver

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[1] Lodge *Society* of *Arts*, 1888.

> (apparently the most difficult of the problems to be solved) would not need to be so delicate as when the rays to be picked up are simply radiating into space in all directions, and fading away according to the law of inverse squares.
>
> I assume here that the progress of discovery would give instruments capable of adjustment by turning a screw or altering the length of a wire, so as to become receptive of wave-lengths of any preconcerted length. Thus, when adjusted to 50 yards, the transmitter might emit, and the receiver respond to, rays varying between 45 to 55 yards, and be silent to all others. Considering that there would be the whole range of waves to choose from, varying from a few feet to several thousand miles, there would be sufficient secrecy, for curiosity the most inveterate would surely recoil from the task of passing in review all the millions of possible wave-lengths on the remote chance of ultimately hitting on the particular wave-length employed by his friends whose correspondence he wished to tap. By " coding " the message even this remote chance of surreptitious straying could be obviated.
>
> This is no mere dream of a visionary philosopher. All the requisites needed to bring it within the grasp of daily life are well within the possibilities of discovery, and are so reasonable and so clearly in the path of researches which are now being actively prosecuted in every capital of Europe that we may any day expect to hear that they have emerged from the realms of speculation into those of sober fact. Even now, indeed, telegraphing without wires is possible within a restricted radius of a few hundred yards, and some years ago I assisted at experiments where messages were transmitted from one part of a house to another without an intervening wire by almost the identical means here described.

The statement in the last paragraph of the quotation refers to the work of Professor David E. Hughes.[1]

Professor Dolbear also suggested the same thing in an article in Donahoe's Magazine, March, 1893.

In fact the idea of using Hertzian waves for wireless telegraphy seems to have been quite widespread in the years immediately following Hertz's publications.

Fairly efficient means of generating electromagnetic waves of any desired length had been made known by Hertz. Vertical antennas connected with the ground had been previously used for sending and receiving by Dolbear in 1882 in connection with his system for telegraphing by electrostatic induction[2] and also later by Edison and others.

Hertz's receiver, the minute spark-gap, was not suited for wireless telegraphy and before any telegraphic work could be done a suitable receiver had to be found.

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1. For Report of this work see *Electrician*, May 5, 1899.
2. Dolbear U. S. patent 350,299, March 24, 1882.

The fact that tubes containing conducting powders had their resistance altered by the discharge of a Leyden jar and that the original resistance could be restored by tapping the tube was first noted by Munk in 1835.[1]

In 1890 Branly showed that such a tube would respond to sparks produced at a distance from it.[2]

In 1892, at the meeting of the British Association at Edinburgh, Professor George Forbes suggested that such a tube would respond to Hertzian waves.

In 1893 Professor Minchen demonstrated experimentally that such powders would respond to electromagnetic waves generated at a distance.[3] He used a battery and galvanometer shunted around the powder to detect the effect of the waves.

Sir Oliver J. Lodge on June 1, 1894, delivered a lecture before the Royal Institution.[4] In this remarkable lecture Lodge described among other things the following:

1. The filings coherer.
2. The filings coherer in hydrogen under reduced pressure (this in a note added July, 1894).
3. The automatic tapper back for the coherer.
4. The metallic reflector for focusing the waves.
5. The connection of the coherer to a grounded conductor; *i.e.*, a gas pipe system.
6. The method of making the coherer so connected respond by setting up oscillations in a separate grounded system, *i.e.*, a hot-water pipe system, in another part of the building.
7. The method of detecting distant thunder storms by connecting the coherer to a grounded gas pipe system.

In this lecture Professor Lodge stated that in his estimate the apparatus used would respond to signals at a distance of half a mile.

Early in 1895 Professor Popoff[5] of Cronstadt, Russia, constructed a very sensitive filings coherer, one form of which was used in some surveying experiments by the Russian government,[1] consisting of iron filings suspended by a magnet and resting upon a metallic plate or cup. Other forms consisted of filings in glass tubes with platinum electrodes. He used early in 1895, the automatic tapping back mechanism, and substituted for the galvanometer an ordinary telegraphic relay. He operated this apparatus at a distance by means of a large Hertzian radiator. One terminal of his coherer was connected to a conductor fastened to a mast about 30 ft. high on the top of the Institute building and the other terminal of the coherer was grounded.

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[1] See Guthe "Coherer action" *Transactions of the International Electrical Congress*, St. Louis, 1904, page 242. *Munck. Poggendorff Ann.* 1838, *Vol.* 43, *p.* 193.

[2] Branley, *Comtes Rendues*, 1890, page 785, and 1891, page 90.

[3] Minchen, *Proceedings Physical Society*, London 1893, page 455.

[4] Sir O. J. Lodge, " The Work of Hertz ", *Proceedings Royal Institution*, June 1, 1904, Vol. 14, page 321.

[5] *Journal Russian Physico-Chemical Society*, Vol.27. April 25,1895,

At the conclusion of his paper, which is dated December, 1895, Popoff made the following statement "In conclusion I can express the hope that my apparatus, with further improvements of same, may be adapted to the transmission of signals at a distance by the aid of quick electric vibrations, as soon as the source of such vibrations, possessing sufficient energy, will be found."

Among other experimenters who were working on this subject at the same time may be mentioned Captain Jackson of the British Navy, and Mr. A. C. Brown.

Marconi, on June 2, 1896, filed a provisional specification[2] showing two forms of apparatus, one similar to Lodge's 1894 apparatus using ungrounded aerials for both sending and receiving and the other for use "when transmitting through the earth or water" substantially identical with Lodge's 1894 and Popoff's 1895 apparatus, with tapper back etc., and the receiving antenna only being grounded.

Soon after, in July 1896, Marconi arrived in England and made a number of experiments for the English Post Office at Salisbury Plain and elsewhere, using ungrounded aerials and parabolic reflectors and succeeded in reaching nearly two miles.

On March 2, 1897, Marconi filed the complete specification in which was included a statement that the transmitting antenna also could be grounded.

Lodge filed a provisional specification[3] showing radiating spheres but no antenna on May 10, 1897. The complete specification filed on Feb. 5, 1898, shows as one form both antennæ grounded and also the use of an inductance wound in the form of a coil for the purpose of diminishing the rate of damping of the waves.

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[1] A. S. Popoff, "Apparatus for detection and registration of electrical vibrations", *Journal Russian Physico-Chemical Society*, Vol. 28, Dec. 1895.

[2] Marconi, Great Britain patent, 12,039, 1896.

[3] Lodge, Great Britain, patent, 11,575, 1897.

So far as is known little work was done in America during this period. The writer made some experiments in 1896 and in conjunction with two of his students, Messrs. Bennett and Bradshaw, did considerable work on receivers of various type in the fall of 1896 and spring of 1897, the results of which were incorporated in a thesis.[1]

3. 1898. *Return to First Principles and Foundation, on lines Antithetical to Old, of New or Sustained Oscillation non-microphonic Receiver Method.* Up to the year 1898, as may be seen from the above, the development of wireless telegraphy had proceeded along a single line. In that year, however, an entirely new method of wireless telegraphy was developed, characterized by a return to first principles, the abandonment of the previously used methods and by the introduction of methods in almost every respect their exact antitheses.

While the coherer is of more or less interest theoretically it is not adapted for use for telegraphic purposes. Responding as it does to voltage rises above a certain limit it does not discriminate between impulses of different characters, and is therefore peculiarly susceptible to interfering signals and atmospheric disturbances, and the operation of coherer systems cannot be guaranteed during the summer months or in the tropics. Roughly speaking a coherer acts by starting an arc and making a short-circuit on the line every time a signal is received, which short-circuit persists until it is broken by a blow from an additional mechanism, and such a method of operation is obviously far from practical. In addition it is practically impossible to obtain sharp tuning in a local circuit containing a coherer; its action is always more or less erratic, its electrostatic capacity variable, and it is insensitive.

At the sending end the energy which can be liberated by the discharge of an antenna is limited and in the form used prior to 1897 the dampening is so great that there are only a few oscillations per spark.

Lodge[2] by placing a coil of large inductance in the antenna throttled down the amount of energy radiated per oscillation and so obtained with the same limited amount of energy derived from the charged antenna, an increase in the time of damping.

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[1] Western University of Pennsylvania, May, 1897.

[2] Lodge, Great Britian, patent 11,575, 1897.

Braun[1] patented the method of using a local oscillatory circuit connected to an antenna, the local oscillatory circuit having a much longer period than the natural period of the antenna and of a different order of magnitude. Such a system, however, does not radiate energy appreciably, and produces a damped wave.

This dampening and the limited amount of energy obtainable by charging and discharging the antenna operates to prevent sharp tuning and working over long distances.

The coherer is well adapted for working with damped waves, but the coherer-damped wave method can never be developed into a practical telegraph system. It is a question whether the invention of the coherer has not been on the whole a misfortune as tending to lead the development of the art astray into impracticable and futile lines and thereby retarding the development of a really practical system.

The fact that no coherer-damped wave system could ever be developed into a practically operative telegraph system, and the fact that it was necessary to return to first principles and initiate a new line of development along engineering rather than laboratory lines was perceived in America in 1898[2] and a new method was advised which may be called the Sustained Oscillation-non-microphonic Receiver method as opposed to the Damped Oscillation-coherer method previously used.

4. *Fundamental Differences between the Old and New Wireless Schools*. The differences between the two methods are shown in tabulated form:

| | Damped Oscillation-coherer Method | | Sustained Oscillation-non-microphonic Method. |
|---|---|---|---|
| A1: | Damped oscillations are produced at the sending end. | A1: | Sustained oscillations are produced at the sending end. |
| 2: | The energy transmitted is obtained by charging the antenna and discharging it. | 2: | The energy transmitted is derived from a local source and fed into the antenna. |
| 3: | A spark gap is used for producing the oscillations. | 3: | An arc or high frequency dynamo is generally used for producing the oscillations. |

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[1] Braun, German patent 11,578, Oct. 14, 1898.

[2] *Electrical World*, July 29, Aug. 12, Sept. 16, 1899 and *Proceedings American Institute of Electrical Engineers*, Nov. 1899, p. 635 and Nov. 20, 1906, p. 731.

| | | | |
|---|---|---|---|
| B1: | Imperfect or microphonic contact receivers are used. | B1: | Non-microphonic contact receivers are used. |
| 2: | The action of the receiver depends upon the voltage rise and is independent of the amount of energy received. | 2: | The receiver response is determined by the integral amount of energy received. |
| 3: | An open tuned circuit is used for receiving. | 3: | A closed tuned circuit is used for receiving. |
| 4: | The receiving circuit is tuned to the wave frequency only. | 4: | The receiving circuit may be tuned to a group frequency as well as to the wave frequency. |
| C1: | In transmitting messages the production of the electromagnetic waves is intermittent. | C1: | The waves are preferably generated continuously and the transmission accomplished by changing the character of the wave. |
| 2: | The wave energy flux is intermittent. | 2: | The wave energy flux is constant. |
| 3: | A high voltage is used. | 3: | A low voltage is used. |
| 4: | Comparatively short wave lengths are used. | 4: | Comparatively long wave lengths are used. |
| 5: | The signals consist of dots and dashes, whose interpretation is fixed. | 5: | The signals may consist of dots only, whose interpretation depends on the station sending and receiving. |
| D1: | Antennæ are used adapted, roughly speaking, to utilize the electrostatic component of the electromagnetic waves. | D1: | The antennæ are preferably arranged so as to utilize the other component of the electromagnetic waves instead of the electrostatic component. |

The history of these two antithetical lines of development will be treated of separately.

5. *Period* 1898–1902 A. *Development and Perfecting of Sustained Oscillation-non-microphonic Receiver Method* (a) *The current-operated receiver.* The first essential for the development of the system was, of course, a quantitatively responsive receiver. Several forms of this were tried including the modification of the Boys' radio-micrometer (consisting of a light thermo couple suspended in the field of a permanent magnet

and heated by radiation from a wire which in turn was heated by the current to be detected) described by the writer at the Columbus meeting of the American Association in 1897.[1] This was abandoned in favor of Professor Elihu Thomson's alternating-current galvanometer[2] suitably modified for telegraphic work.[3]

Among other forms of current-operated receiver may be mentioned the following.

The *Hot-wire Barretter*,[4] consisting of a minute platinum wire a few hundred thousandths of an inch in diameter and approximately a hundredth of an inch in length. The term " barretter " was coined for this device for the reason that it differs essentially from the bolometer of Langley in that it is arranged to be affected by external sources of radiant heat as little as possible instead of as much as possible, and, to have an extremely small specific heat, an object not sought in the case of the bolometer.

The *Liquid Barretter*[5] in which the change of resistance is effected by heating a liquid, the concentration of path being obtained by means of a fine platinum wire point. Some question has been raised as to the theory of operation of this device but I think there is no question but that the effect is due to heat, though what per cent. of the effect is due to change in ohmic conductivity by heat and what per cent. is due to depolarization by heat is still, as originally stated by the writer,[6] uncertain. The facts that the device operates practically equally well irrespective of which terminal is connected to the local battery, and that the effect varies as the square of the alternating current (as a heat operated device should do) instead of directly with the alternating current as a rectifier would do, and that depolarization is produced by the heat, have been confirmed by Dr. L. W. Austin.[7] The writer has experimentally determined the fact that though the electrical impulses may have a duration of less than a millionth part of a second the change in resistance persists for approximately the ten thousandth part of a second, which would seem to show conclusively that the action is not a *direct* effect of the waves.

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[1] *Electrician*, June 24, 1904.

[2] Elihu Thomson, U. S. patent 363,185, Jan. 26, 1887.

[3] U. S. patents 706,736 and 706,737, Dec. 15, 1899.

[4] U. S. patent 706,744, June 6, 1902.

[5] U. S. patent 727,331, April 9, 1903.

[6] *Ibid*.

[7] Austin, *Bulletin of the Bureau of Standards*, Vol. 2 No. 2.

The term electrolytic receiver has sometimes been applied to the liquid barretter. This is objectionable, as there are a number of electrolytic receivers. For example, the Neughschwender-Schaefer[1] receiver, in which a number of microscopic filaments are produced between two terminals by electrolysis, which filaments are ruptured by the wave produced oscillations, thus increasing the resistance; also the liquid coherer of Captain Ferrie, described by him as follows:[2]

> The same effect of self-decohering coherence has been determined for a contact of a metallic wire and a liquid conductor, acidulated water, contained in a glass tube of small diameter, and placed under the same conditions as the preceding. Always, the sensitiveness of this contact is very notably inferior to that obtained in the experiments disclosed above. The maximum sensitiveness was obtained when the resistance of the imperfect contact was about 2000 ohms and when the extremity of the metal wire scarcely grazed the meniscus of the liquid. The results obtained were better with a copper wire, attacked by the acidulated water, than with a platinum wire.

which probably acts through a chemical effect producing a thin film of gas and has never come into use, doubtless because, as Captain Ferrie points out, it is even less sensitive than the Marconi coherer. Also the rectifier of Pupin[3] in which the terminals are placed so closely together that practically no energy is absorbed in the receiver, in order that the rectified energy may be utilized outside in the external circuit, in opposition to the liquid barretter, where the position of the terminals is such that all the received wave energy is absorbed in the barretter for the purpose of producing a secondary effect, and so influencing the current in a shunted local circuit.

(b) *Methods of Obtaining Sustained Oscillations.* 1. *Spark-gap and Local Oscillatory or "tank" Circuit.* Professor Elihu Thomson discovered that by using a transformer without an iron core (the well known Elihu Thomson air-core transformer, later used by Tesla and others), and a spark-gap and condenser in the primary circuit and with the secondary circuit suitably tuned great resonant rises of potential could be obtained. In 1892 he constructed such a transformer giving discharges 64 inches long.[4]

The same method was later used by Tesla[5] in his experimental researches and in his attempt to carry out Loomis'[1] method of transmitting a current through a hypothetical conducting stratum in the upper regions of the atmosphere.

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[1] Neughschwender German Patent 107843, Dec. 13, 1898, and Schaefer British Patent 6002, 1899.

[2] Blondel, *L'Eclairage Electrique*, Sept. 29, 1900.

[3] Pupin, U. S. Patent 713,044, January 4, 1898.

[4] *Electrical World*, Feb. 20 and 27, 1892.

[5] U. S. patent 645,516, Sept. 2, 1897.

The device, suitably modified for wireless telegraphic purposes, so as to give instead of a continuously cumulative rise of potential an initial rise of potential followed by a gradual feeding in of the energy from the local circuit to supply the energy lost from radiation, was made use of in 1898 for the purpose of producing prolonged trains of sustained waves.

Various types of connection between the antenna and the local oscillatory circuit were tested but it was found that the most efficient results were obtained by connecting the local circuit directly across the spark-gap.[2]

The results of some comparative tests are here given. The figures in the column " A " are for the local circuit connected directly to the terminals of the spark-gap, those in column " B " are for an auto-transformer, those in column " C " for a loose coupled primary and secondary.

| | A | B | C |
|---|---|---|---|
| Frequency........ | 212,000 | 212,000 | 212,000 |
| Tank capacity..... | 0.072 m.f. | 0.072 m.f. | 0.072 m.f. |
| Kilowatt output dynamo........... | 30 | 30 | 30 |
| Tank current....... | 400 amperes | 370 amperes | 300 amperes |
| Antenna current... | 48.5 | 46. | 48. |

The large station at Brant Rock is operated with the local circuit directly connected across the spark-gap, partly because the efficiency is somewhat greater, but also on account of the great simplification of connections and the fact that the degree of sustainment of the wave train may be adjusted very simply, if desired, by sliding the lower terminal of the antenna along a few inches of the lead of the local oscillatory circuit.

Cooper Hewitt[3] in 1902 used a modification of his mercury lamp to obtain intermittent discharges each followed by a train of high frequency oscillations.

2. *Arc methods.* The worker with high frequency oscillatory currents will soon discover that we are indebted to the genius of Professor Elihu Thomson for practically every device of any importance in this art.

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[1] Loomis, U. S. patent, 129,971, July 30, 1872.

[2] U. S. patents 706,735 and 706,736, Dec. 15, 1899.

[3] Cooper Hewitt, U. S. patent 780,999, April 25, 1902.

The method of producing high frequency oscillations from an arc and continuous current was discovered by him in 1892.[1] Fig. 1, taken from his patent, shows the general form of his arrangement. If the directions given in the specification are followed no difficulty will be met with in obtaining frequencies as high as 50,000 per second.

Between 1900 and 1902 some experiments were carried out with the Elihu Thomson arc as a source of high frequency oscillations for wireless telegraphy and telephony.

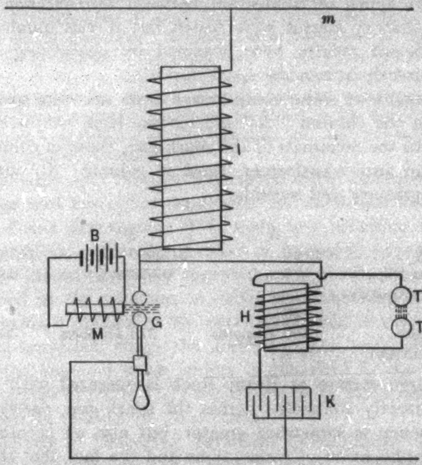

Fig.1

Some difficulties were found, for example the arc could not be started and stopped as quickly as was necessary for telegraphic purposes and the intensity of the oscillations and their frequency varied considerably. These were overcome by making some minor improvements, for example the difficulty in sending was overcome by permitting the arc to run continuously and using the key to change the electrical constants of the circuits.[2] The difficulty in keeping the intensity and frequency constant was overcome by substituting resistance for a portion of the inductance, and also by using the arc under pressure.[1]

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[1] Elihu Thomson U. S. patent 500,630, July 18, 1892.

[2] U. S. patents 706,742, July 6, 1902, 706,747, Sept. 28, 1901, 727,330, March 21, 1903, 730,753, April 9, 1903.

Tests made by Dr. Austin[2] show that with this method frequencies as high as 3,000,000 per second and efficiencies as high as 60% can be obtained together with an absolutely steady[3] generation of the high frequency currents and an absence of harmonic frequencies.

3. *High frequency alternator.* The first high frequency alternator was built by Professor Elihu Thomson in 1889. And it[4] was while experimenting with it in 1900 that Dr. Tatum made his very interesting discovery that high frequency currents of large amperage could be passed through the body without injury.[5]

FIG. 2

From 1898 to 1900 numerous experiments were made on antennæ of large capacity and it was found that instead of using sheets of solid metal or wire netting, single wires could be placed at a considerable fraction of the wave-length apart and yet give practically the same capacity effect as if the space between them were filled with solid conductors.

From other investigations on the variation of radiation with frequency the result was arrived at that it should be possible to construct an alternating-current dynamo of sufficiently high frequency and output to give ample radiation for wireless telegraphic purposes.[1]

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[1] *Ibid* and U. S. patent 706,741.

[2] Austin, *Bulletin of the Bureau of Standards*, Vol. 3, No. 2.

[3] Austin assumed from the figure he obtained for the dampening, that the oscillations were not continuous; but the method used for determining the dampening is not applicable to this case, and a comparison of the currents and voltages with the frequencies given in Austin's experiments, shows that these oscillations must have been continuous.

[4] Thomson, *Elec.Engineer*, July 30,1890 and *London Elec.*,Sept.12,1890.

[5] Thomson, *Elec. Engineer*, March 11, 1891.

In 1900 a large American electrical manufacturing company kindly consented to take up the construction of such a dynamo. As a preliminary, a dynamo of 1 kw. output and 10,000 cycles (shown in Fig. 2) was built in 1902. By the summer of 1906 many of the difficulties had been overcome and a machine giving 50,000 cycles was installed at the Brant Rock station. Various improvements were made by the writer's assistants, and in the fall of 1906 the dynamo was working regularly at 75,000 cycles, with an output of half a kilowatt and was being used for telephoning to Plymouth, a distance of approximately 11 miles. In the following year machines were constructed having a frequency of 100,000 cycles per second and outputs of 1 and 2 kilowatts.

The credit for the development of this machine is due to Messrs. Steinmetz, Haskins, Alexanderson, Dempster, and Geisenhoner and also to the writer's assistants, Messrs. Stein and Mansbendel.

(*c*) *Closed tuned circuits.* In 1898 the open tuned circuits originally used were discarded for closed tuned circuits[2] and it was discovered that valuable selective effects could be obtained by placing the condenser in shunt to the inductance instead of in series with it.[3]

(*d*) *Combination of wave and group tuning.* The fact that if selectivity is obtained solely by tuning to wave frequencies, the number of stations is limited, was appreciated at an early date. In 1900[4] a new method was developed, the stations being tuned both to the wave frequency and to an independent or group frequency, so that stations might obtain selectivity by varying either the wave or the group frequency and thus have at their disposal a virtually unlimited number of combinations and be practically free from atmospheric disturbances. Fig. 3 shows a type of group tuner.

(*b*) *Further development of damped wave-coherer method.* Marconi by 1898 had carried the development of the filings coherer to its maximum point.

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[1] U. S. patent 706,737, May 29, 1901.

[2] U. S. patents 706,735 and 706,736, Dec. 15, 1899.

[3] *Ibid.*

[4] U. S. patents 727,325, June 2, 1900, and 727,330 March 21, 1903.

Lodge in 1897[1] had disclosed the open secondary circuit for receiving.

Marconi in 1898[2] greatly improved this by adjusting the length of the secondary so as to tune it, and by the aid of this improvement was enabled to telegraph a distance of 35 miles[3] in October, 1899.

Lodge in 1902[4] invented what is perhaps the most perfect form of coherer, consisting of a thin steel disc dipping in oil covered mercury and automatically decohered by being kept in continuous rotation.

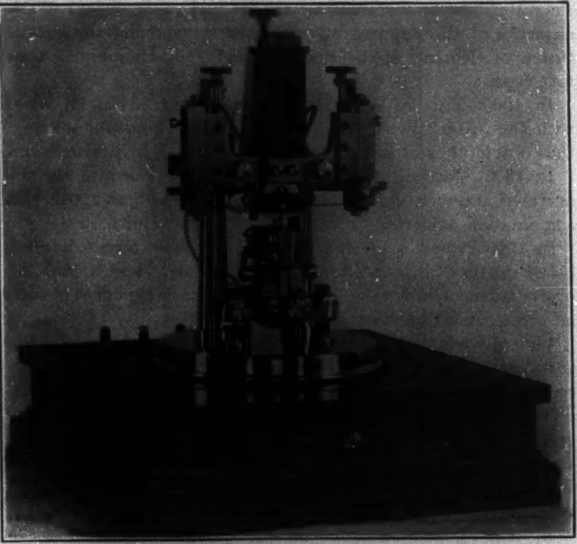

FIG. 3.

A number of self-restoring coherers of which the Brown[5] carbon coherer may be taken as a type, including the mercury carbon coherer of Solari, came into more or less extended use, and also modifications of the imperfect contact receiver of Neugschwender.[1]

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[1] Lodge, Great Britain patent, 11,575, May 10, 1897.

[2] Marconi, Great Britain patent, 12,326, June 1, 1898.

[3] Official report U. S. Navy of test U. S. S. Massachusetts, Oct. 1899.

[4] Lodge, Muirhead and Robinson, Great Britain patent, 13,521, June 14, 1902.

[5] Brown and Neilson, Great Britain patent, 28,955, Dec. 17, 1896.

The small progress made along these lines is to be explained by the fact that the damped wave-coherer system is essentially and fundamentally incapable of development into a practical system.

*Period* 1902-1908—*Later Developments.* Progress in Europe since 1902 has been marked by the gradual abandonment of the elements of the damped wave-coherer system and the substitution of elements of the sustained wave non-microphonic contact type.

In 1900[2] Marconi substituted for the plain aerial an aerial with the writer's tuned local circuit or tank circuit for sending, thus obtaining a considerable increase in range of transmission.

In 1902, Marconi invented a very ingenious form of current operated receiver, called the magnetic detector[3], and with this combination achieved some very remarkable results.

In 1905 Professor Fleming[4] invented a very efficient detector based on the "Edison effect" in incandescent lamps, and the observations of Elster and Geitel[5] on the rectifying effect of such an arrangement on Hertzian oscillations.

Virtually nothing was done in Europe in the way of producing sustained oscillations by the arc or high frequency method until recently, possibly because of Duddell's erroneous statement[6] to the effect that frequencies much above 10,000 could not be obtained by the Elihu Thomson arc method, and Fleming's statement[7] that an abrupt impulse was necessary and that high frequency currents, even if of sufficient frequency, could not produce radiation.

In 1903 Poulsen[8] invented an interesting modification of the Elihu Thomson arc, which consists in forming the arc in hydrogen instead of in air or compressed gas as previously done. This modification is not, however, so efficient as the older methods and gives oscillations varying in amplitude and intensity and accompanied by strong harmonics,[1] but I have considered it worth mentioning on account of the amount of interest it appears to have excited in Europe.

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[1] A. Neugschwender, *Wied. Ann. der Physik*, 1899, vol. 67, p. 430. Schafer, British patent, 6,002, 1899.

[2] Marconi, Great Britain, patent, 7,777, Apr. 26, 1900.

[3] Marconi, Great Britain, patent, 10,245, 1902.

[4] Fleming, *Proceedings Royal Society London*, 1905, Vol. 74.

[5] Elster and Geitel, *Wied. Ann der Physic*, Vol. 52, page 433.

[6] Duddell, *The Electrician*, 1903, Vol. LI, page 902.

[7] Fleming, *Proceedings of the International Congress, St. Louis*, 1904, Vol. 3, page 603.

[8] Poulsen U. S. patent 789,449, June 19, 1903.

Some very important and interesting papers on electrical oscillations were published during these years by Oberbeck,[2] Wien,[3] Drude,[4] and Bjerknes.[5]

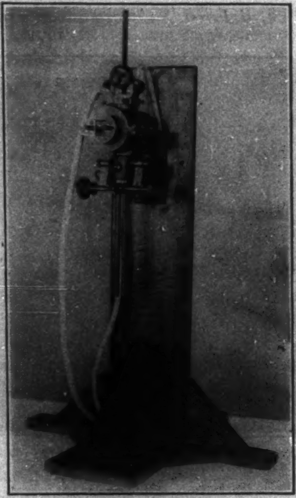

Fig. 4.

In America the development of the sustained oscillation non-microphonic system has proceeded steadily and it may now be said to have reached the stage of commercial practicability. On account of the amount of work which has been done it is impossible to refer to more than a few of the recent advances.

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1. Austin, *Bulletin of the Bureau of Standards*, Vol. 3 No. 2.
2. Oberbeck Wied. *Ann. der Physik*, Vol. 55, 1895.
3. *Wied Ann. der Physik* Vol. 8, 1902.
4. Drude *Ann. der Physik*, Vol. 13, 1904.
5. Bjerknes, *Ann. der Physik*, Vol. 44, 1891, and Vol. 47, 1892.

The following are some of the later types of detectors:

The *frictional receiver*,[1] in which the waves produce a change of friction between two moving surfaces and so cause an indication.

The *heterodyne receiver*,[2] in which a local field of force actuated by a continuous source of high frequency oscillations interacts with a field produced by the received oscillations and creates beats of an audible frequency.

The so called *thermoelectric receivers* of Austin,[3] Pickard[4] and Dunwoody.[5]

The "*audion*" *of deForest*,[6] a very interesting and sensitive device, which though superficially resembling Professor Fleming's rectifier appears to act on an entirely different principle.

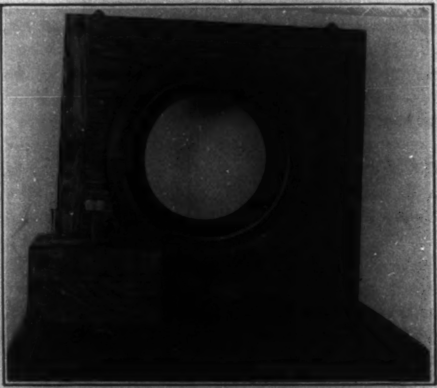

FIG. 5.

The *Cooper Hewitt mercury receiver*, about which little is known but which appears to be very sensitive.

The following are some of the later methods of producing sustained oscillations:

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1. U. S. application, 251,538, March 22, 1905.
2. U. S. application, 271,539, June 28, 1905.
3. Austin, U. S. application, 319,241, May 29, 1906.
4. Pickard, U. S. application, 342,465, Nov. 8, 1906.
5. Dunwoody, patent, 837,616, March 23, 1906.
6. deForest, U. S. patent, 836,070, Jan. 18, 1906.

The *substitution of a number of arcs in series having terminals of large heat capacity* in place of the single arc in the arc method.[1]

The *use of regulating or "fly-wheel" circuits* in connection with the arc method.[2]

The *method of producing oscillations* shown in Fig. 4 by using two arcs and throwing the discharge from one side to the other alternately at a frequency regulated by the constants of the electric circuit.[3]

The *condenser dynamo*[4] which consists of two radially slotted discs separated by a mica diaphragm, charged by a continuous current source of potential, and rotating in opposite directions.

*Two-phase high frequency dynamo method.*[5]

*Commutator method.*[6] In this method the high frequency is produced by means of a ball rotating at high speed on the interior surface of a commutator. Shown in Fig. 5.

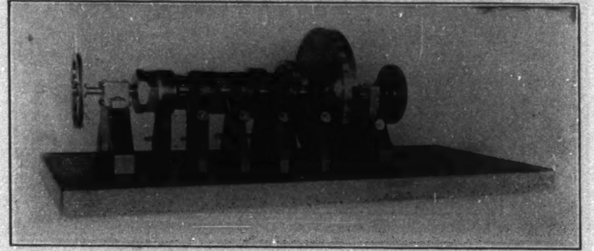

FIG. 6.

The *helium arc method*[7] in which the arc is produced in helium or argon or similar gases.

The *critical pressure method*[8] in which the electrodes extend within a certain critical distance, depending upon the pressure used, so that the discharge always passes at the same voltage irrespective of the distance between the electrodes.

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[1] U. S. application, 291,737, Dec. 14, 1905.

[2] *Ibid.*

[3] *Ibid.*

[4] U. S. application, 291,739, Dec. 14, 1905.

[5] U. S. patent, 793,649, March 30, 1905.

[6] U. S. application, 316,521, May 12, 1906.

[7] U. S. application, 351,560, Jan. 7, 1907.

[8] U. S. application, 355,787, Feb. 4, 1907.

*Methods of Signaling. Continuous production of waves* but changing constants of sending circuit.[1]

The *inverted method* of sending and the method of signaling by sending dots, the interpretation of which is determined by similar commutators at the sending and receiving stations.

*Duplex and Multiplex Methods.* A considerable number of these have been worked out, mostly operating either by balance methods[2] or commutators.[3] It is impossible to discuss all the various improvements, such for example as the method of indicating the busy and free state of a station, the methods of sending and receiving in one direction, the various types of aerials used for receiving the other components of the electromagnetic waves besides the electrostatic component, etc.

FIG. 7.

Fig. 6 shows the harmonic interrupter for determining the variation of intensity with change of note.

Fig. 7 shows a type of receiver described in U. S. Patent 706,747, in which the telephone diaphram is formed of thin copper and repelled by a fixed coil having a resistance of about 16 ohms. The principle of this receiver was discovered by Professor Elihu Thomson. It has been used for wireless telephony for a distance of 11 miles with fairly satisfactory results.

Fig. 8 shows a transformer used in the transmitting circuit. The number of primary and secondary turns can be altered continuously, and also the degree of coupling. The wire is

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1. U. S. patents 706,747, Sept. 28, 1901; 706,742, June 6, 1902; 727,747, March 21, 1903.

2. U. S. application, 366,528, April 5, 1907.

3. U. S. patent, 793,652, April 6, 1905.

wound off from an insulating cylinder onto a cylinder of copper, and the cylinder of copper, forming a closed circuit secondary of the transformer, annuls the inductance of that portion of the wire wound upon the copper cylinder.

Fig. 9 shows an apparatus for determining the best shape of coil for use with the heterodyne receiver.

Fig. 10 shows a group-tuned call; that is, a vibration galvanometer which operates a selenium cell and rings a bell when a call is received.

## C. THEORY OF WIRELESS TELEPHONY

For wireless telephony three things are necessary:

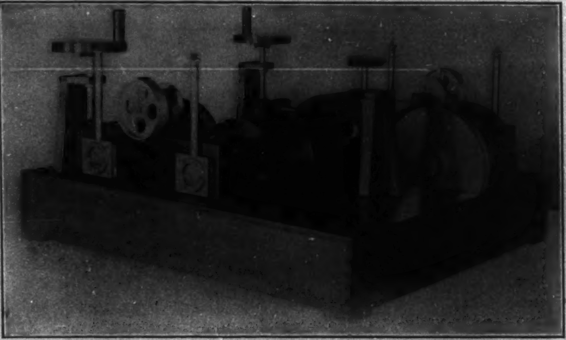

FIG. 8.

1. Means for radiating a stream of electrical waves sufficiently continuous to transmit the upper harmonics on which the quality of the talking depends.
2. Means for modulating this stream of waves in accordance with the sound waves.
3. A continuously responsive receiver giving indications proportional to the energy received, and capable of responding with sufficient rapidity to the speech harmonics.

Work on the wireless telephone was commenced before a satisfactory means was discovered for producing sustained oscillations.

To ascertain the number of sparks per second which was necessary to determine articulate speech, a phonograph cylinder was taken and grooves were cut in it longitudinally. It was found in this way that practical transmission could be accomplished with 10,000 breaks per second. It is believed now that this number is unnecessarily high, possibly owing to the fact that it was impossible to cut the grooves on the cylinder without producing ridges. The lower limit may be fixed in another way.

Electrical circuits met with in actual working have resistance, self inductance capacity, and leakance. Heaviside gave the differential equations for the pressure and current over such circuits when alternating voltages were applied, but no method of solution being known the mathematical treatment of such circuits was restricted to cases where one of the constants was neglected, until Dr. A. E. Kennelly in a masterly series of papers gave the complete solution.

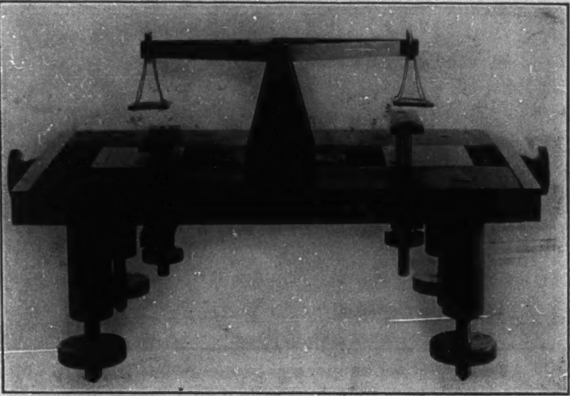

FIG. 9.

The results were immediately found applicable to a great variety of problems, such as the transmission of signals through cables and of telephonic speech through various types of circuits.

In this way Dr. Kennelly[1] by comparing the results obtained by Dr. Hammond V. Hayes[2] in practical telephonic transmission

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[1] Kennelly, " Distribution of Pressure and Current over Alternating Current Circuits ", *Harvard Engineering Journal*, 1906, page 43.

[2] Hayes, " Loaded Telephone Lines in Practice ", *Transactions International Electrical Congress*, St. Louis, Vol. 3.

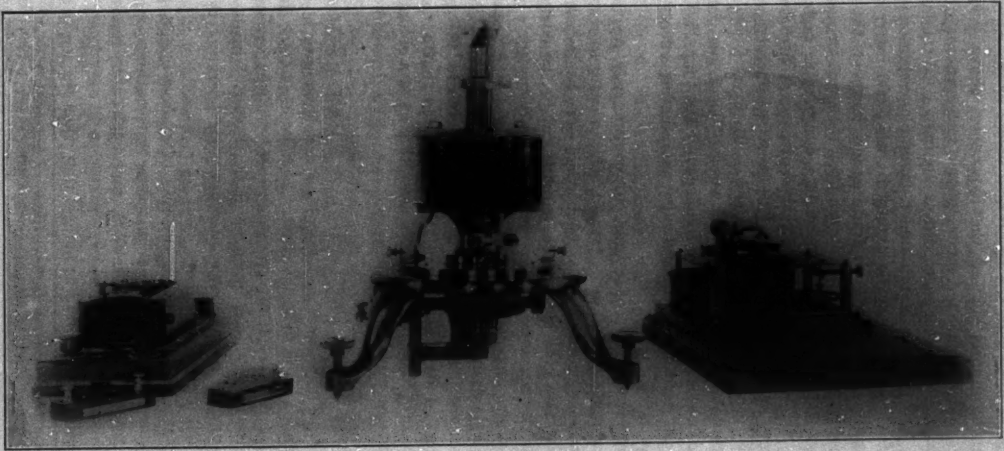

FIG. 10.

over loaded lines with the theoretical values of the current for different harmonics showed that harmonics above 2,000 per second could be neglected for telephonic transmission.

The writer has never succeeded in obtaining good talking with such a low frequency, but under favorable conditions fairly satisfactory speech may be obtained with 5,000 interruptions per second. For really good transmission, however, the radiation must be practically continuous, for if the spark frequency is less than 20,000 per second there is a disagreeable high pitch note in the telephone, not noticeable perhaps at first but apt to become annoying with use. The most satisfactory way is, of course, to use a source of sustained oscillations.

It fortunately happens that for wireless telephonic purposes it is inadvisable to use a wave frequency of less than 25,000 per second, on account of the difficulty in radiating energy with low frequencies.

The receiver must, of course, be continuously responsive. If, for example, it had to be tapped back in order to restore it to the responsive condition, speech could not be transmitted.

It must also give indications proportional to the energy received or the character of the speech will be distorted.

It must also respond with sufficient rapidity. If, for example, it takes a thousandth of a second to restore itself to its original resistance the receiver will obviously not record the higher harmonics. I have experimentally determined that a receiver which restores itself in the ten thousandth part of a second acts with sufficient rapidity.

## D. HISTORY OF THE DEVELOPMENT OF WIRELESS TELEPHONY

The writer has been asked on several occasions how the wireless telephone came to be invented. In November, 1899, shortly prior to the delivery of my previous paper,[1] while experimenting with the receiver shown in Fig. 3 of that paper, I made some experiments with a Wehnelt interrupter for operating the induction coil used for sending.

In the receiver mentioned the ring of a short-period Elihu Thomson oscillating current galvanometer rests on three supports, *i.e.*, two pivots and a carbon block, and a telephone receiver is in circuit with the carbon block. A storage battery being used in the receiver circuit[2] it was noticed that when the sending key was kept down at the sending station for a long dash the peculiar wailing sound of the Wehnelt interrupter was reproduced with absolute fidelity in the receiving telephone. It at once suggested itself that by using a source with a frequency above audibility wireless telephony could be accomplished.

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[1] *Transactions American Institute Electrical Engineers*, Nov. 22, 1899.

[2] U. S. patent, 706.736, December 15, 1899.

Professor Kintner, who was at that time assisting me in these experiments and to whose aid their success is very largely due, was kind enough to make the drawings for an interrupter to give 10,000 breaks per second. Mr. Brashear, the celebrated optician kindly consented to make up the apparatus and it was completed in January or February, 1900.

The experimental work was, however, delayed as the writer was at that time transferring his laboratory from Allegheny, Pa., to Rock Point, Md., and it was not until six months later that the stations at that point were completed and a suitable mast was erected for trying the apparatus.

The first experiments were made in the fall of 1900 with the above mentioned apparatus which was supposed to give 10,000 sparks per second but which probably gave less. Transmission over a distance of one mile was attained but the character of the speech was not good and it was accompanied by an extremely loud and disagreeable noise, due to the irregularity of the spark.

By the end of 1903 fairly satisfactory speech had been obtained by the arc method above referred to, but it was still accompanied by a disagreeable hissing noise. In 1904 and 1905 both the arc method and another method in which the 10,000 cycle alternator above referred to was employed, had been developed to such an extent that the apparatus could be used practically and sets were advertised and tendered to the U. S. Government.[1] The transmission was, however, still not absolutely perfect.

By the fall of 1906 the high frequency alternator had been brought to a practical shape and was used for telephoning from Brant Rock to Plymouth, a distance of 11 miles, and to a small fishing schooner,[2] this being the first instance in which wireless telephony was put in practical use. The transmission was perfect and was admitted by telephone experts to be more distinct than that over wire lines, the sound of breathing and the slightest inflections of the voice being reproduced with the utmost fidelity.

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[1] Letter of July 8, 1905; see *The Electrician*, London, Feb. 22, 1907; also catalogue of 1904 and subsequent.

[2] An amusing instance may be mentioned as illustrating the incredulity with which the wireless telephone was received. Some of the local papers having published an account of the experiments with the schooner above referred to the following appeared under the heading

As it was realized that the use of the wireless telephone would be seriously curtailed unless it could be operated in conjunction with wire lines, telephone relays were invented both for the receiving and transmitting ends and were found to operate satisfactorily, speech being transmitted over a wire line to the station at Brant Rock, retransmitted there wirelessly by a telephone relay, received wirelessly at Plymouth and there relayed out again on another wire line. On Dec. 11, 1906, invitations were issued to a number of scientific men to witness the operation of the wireless transmission in conjunction with the wire lines.[1] A report of these tests appeared in the American Telephone Journal of Jan. 26 and Feb. 2. 1907, the editor being one of the men present.

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"Current News and Notes" in the columns of a prominent technical journal, Nov. 10, 1906.

"A New Fish Story.—It is stated from Massachusetts that the wireless telephone has successfully entered into the deep sea fishing industry. For the last week experiments have been conducted by the wireless telegraph station at Brant Rock, which is equipped with a wireless telephone, with a small vessel stationed in the fleet of the South Shore fishermen, twelve miles out in Massachusetts Bay. Recently, it is asserted, the fishermen wished to learn the prices ruling in the Boston market. The operator on the wireless fitted boat called up Brant Rock and telephoned the fishermen's request. The land operator asked Boston by wire and the answer was forwarded back to the fishermen. This is a rather fishy fish story".

The doubt expressed was, however, only natural. I remember the astonishment displayed by one of the company's new operators some months previously on placing the receiving telephone to his head while the vessel was almost out of sight of land and hearing the operator at the land station call his name and begin to talk to him.

[1] Brant Rock, Mass., Dec. 11, 1906.

*American Telephone Journal*, 100 William St., New York City.

Dear Sirs: A limited number of invitations have been issued to witness the operation of the National Electric Signaling Co's. wireless telephone system between Brant Rock and Plymouth, Mass., over a distance of between ten and eleven miles.

The tests will be as follows:

1. Transmission of ordinary speech, and also transmission of phonographic talking and music by wireless telephone between Brant Rock and Plymouth.
2. Transmission of speech over ordinary wire line to wireless station at Brant Rock, relaying the speech there automatically by telephone relay and automatically transmitting the speech by wireless to Plymouth.

In July 1907 the range was considerably extended and speech was successfully transmitted between Brant Rock and Jamaica, Long Island, a distance of nearly 200 miles, in daylight and mostly over land,[1] the mast at Jamaica being approximately 180 ft. high.

In 1907 several European experimenters succeeded in transmitting speech wirelessly, using some of the earlier forms of the writer's arc method, and some months ago the vessels of our Pacific squadron were equipped with wireless telephones, using this arc method, by another American company.

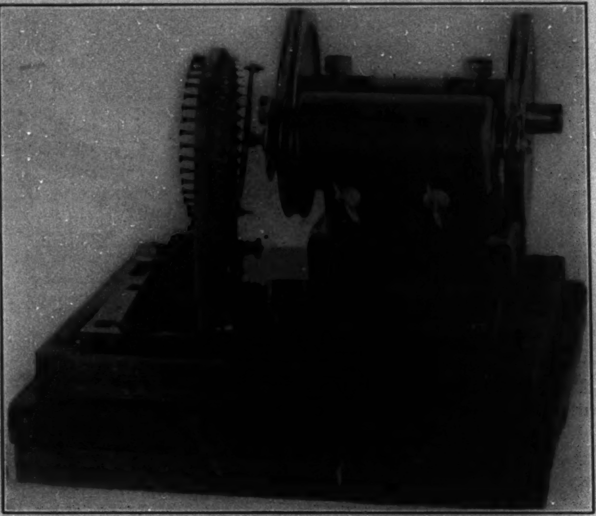

Fig. 11.

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transmitting same at Plymouth automatically directly or by telephone relay over regular wire line.

Invitations have been issued to the following gentlemen, (here follows list of some of the guests, including Dr. A. E. Kennelly, Professor Elihu Thomson, etc., and a request to the company to send a representative).

Yours very truly,
National Electric Signaling Co.

[1] "Long Distance Wireless Telephony," *The Electrician*, Oct. 4, 1907.

### E. METHODS AND APPARATUS

1. *Methods and apparatus for producing the electromagnetic waves.* These have been already referred to. Fig. 11 shows a rotating spark-gap giving approximately 20,000 discharges per second. This was connected to a 5,000-volt source of direct current. The terminals are of 40% platinum-iridium. In operation the apparatus is arranged to charge a condenser to a definite potential and discharge it.

FIG. 12

Figs. 12 and 13 show forms of apparatus for operating the arc in a gas under pressure.

The apparatus of Fig. 13 is also used for the arc in vacuum and the critical distance arc.

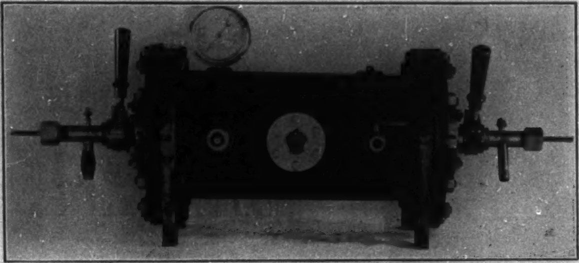

FIG. 13.

Fig. 14 shows a multiple gap with rotating electrodes, brass, amalgamated zinc and graphite being used.

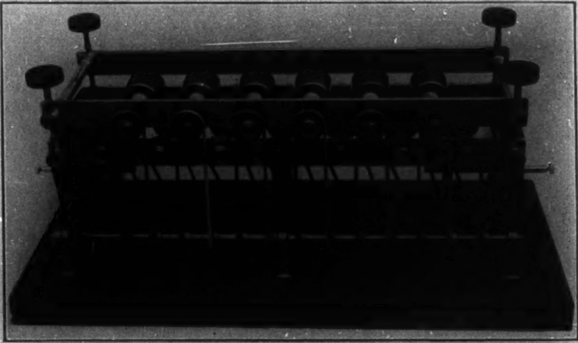

FIG. 14.

Fig. 15 shows a multiple arc gap with electrodes of different materials, the upper terminals being water cooled.

Fig. 16 shows a condenser dynamo.

Fig. 17 shows a general view of one type of high frequency alternator. It is driven by a motor and a DeLaval gear. It has been operated at 96,000 cycles per second, but is generally run at 81,700.

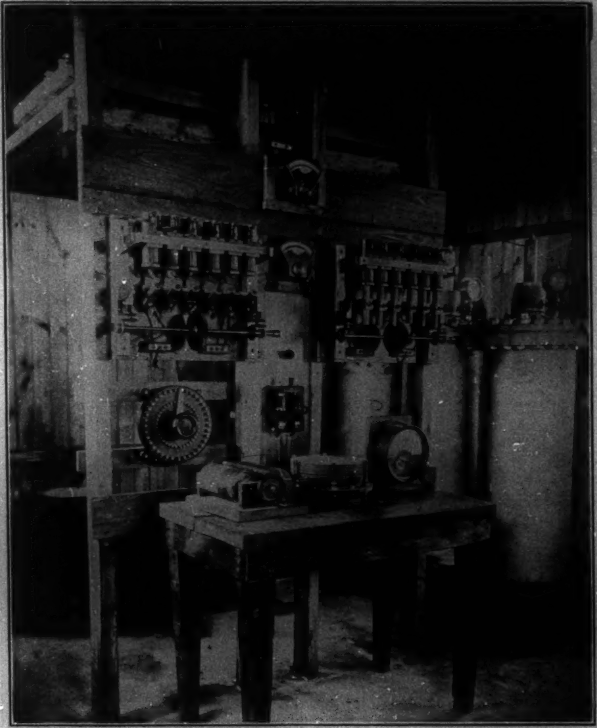

FIG. 15.

Fig. 18 shows a field disc; it is 12 inches in diameter and there are 300 slots on it.

Fig. 19 shows the armature and field coils. There are 600 armature slots each containing two turns of 13 mil wire. The

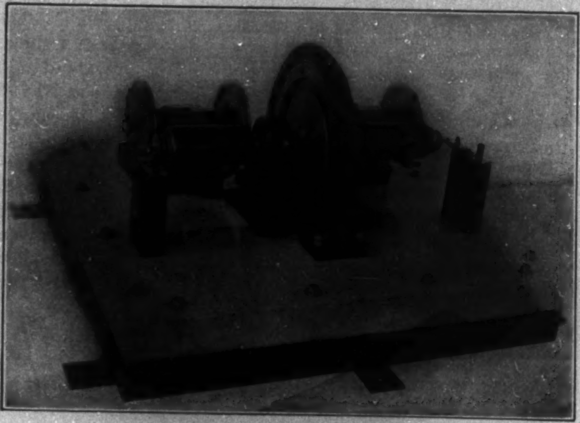

FIG. 16.

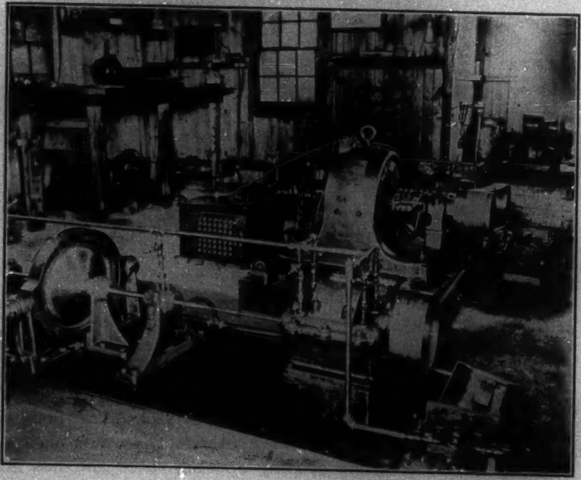

FIG. 17.

field current is 5 amperes. The resistance of the armature is 6 ohms; it gives 160 volts and about 7 or 8 amperes. Other armatures have been constructed having a resistance of 4 ohms. For some work double armatures are used giving about 270 volts. The output of the single armature machines at 81,700 cycles is approximately one kilowatt. The output of the double armature machine is approximately 2 kilowatts.

Other types of high frequency alternators are under construction. One type shown in Fig. 20 is designed for use on shipboard. The armature disc is 6 inches in diameter and two armatures are used. It is arranged to be mounted on gimbals and to be driven by a steam turbine connected to the steam pipe by flexible armored steam hose. The frequency is about 100,000 and the output about 3 kilowatts.

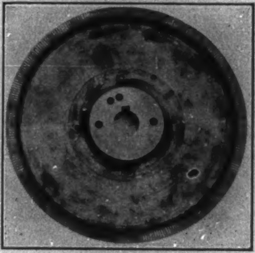

FIG. 18

Another type, which is at present being constructed by Mr. Alexanderson, to whose efforts the success of this type of generator is largely due, is designed to have an output of 10 kilowatts. Designs have been made for a generator of still larger size with a calculated output of 50 kilowatts and a frequency of 50,000. This machine is intended for transatlantic work.

For some of these machines, instead of driving by gear or steam turbine, a special two-cycle motor has been devised, to operate at a frequency of 500 cycles per second.

The high frequency alternator method is believed to possess a number of advantages over other methods, inasmuch as it is set in operation by merely opening a steam valve and has no complicated electrical apparatus or circuits of any kind. The

FIG. 21.

speed is regulated by the steam pressure, this being accomplished by an electrically operated reducing valve.

For measuring the frequency various speed indicators have been tried, but it has been found that the best way is to use a resonant circuit with an ammeter shown in Fig. 21 in it,[1] this being an extremely sensitive means of indicating the frequency and in addition affording a means of automatically keeping the speed constant to a small fraction of a per cent. The reducing valve is adjusted so that if left to itself the machine will run slightly above speed.[2] As soon as it reaches one-tenth of one per cent. higher than its designed speed the resonance begins to fall and a contact is opened which slightly throttles the steam. In

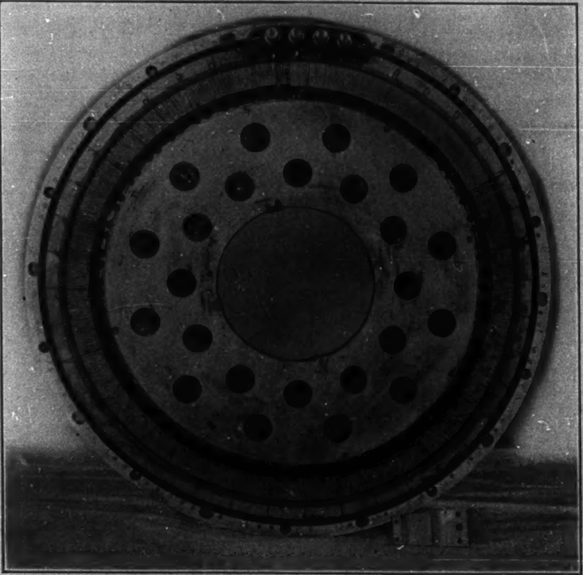

FIG. 19.

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[1] *Electrical World and Engineer*, Nov. 11, 1899.

[2] Since writing the above, my attention has been called to the fact that the general method of governing by resonance was invented and patented by Kempster B. Miller, U. S. patent 559,187, Feb. 25, 1896.

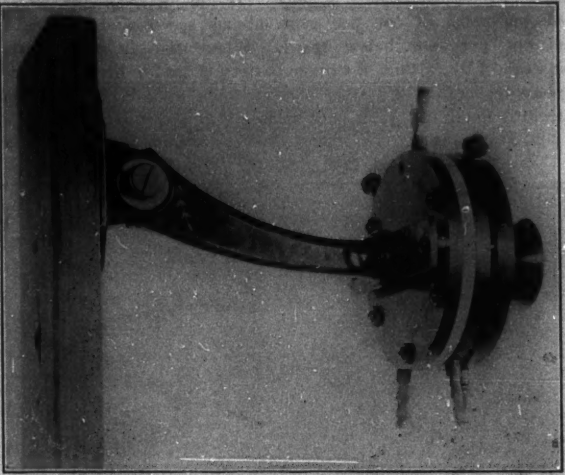

Fig. 20.

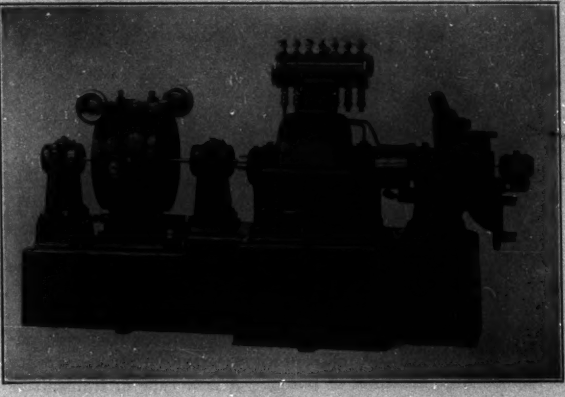

Fig. 22.

this way the frequency is kept varying between the limits of one-tenth of one per cent. above speed and one-tenth of one per cent. below speed. Where the drive is electric instead of by turbine, a storage battery is used to drive the two-phase generator and even better results may be obtained as regards regulation than with steam.

2. *Transmitters.* The types of transmitters most commonly used are the carbon transmitter and static transmitter, and the carbon transmitter relay.

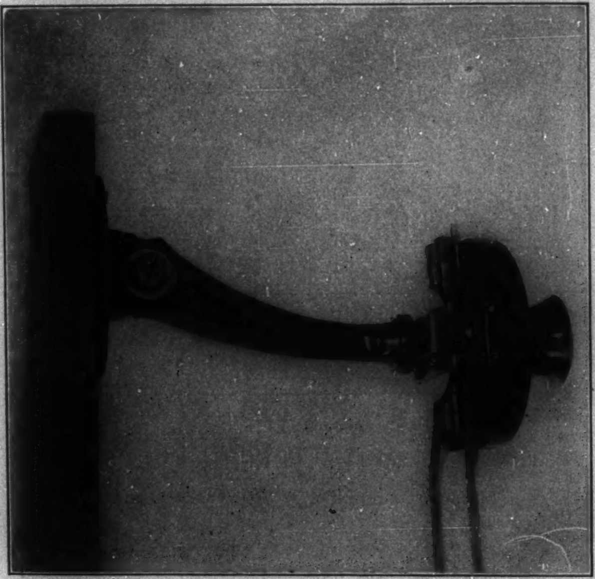

FIG. 23.

Fig. 22 shows the standard type of carbon transmitter.

It was found that the ordinary carbon transmitter was unsuited for wireless telephonic work on account of its inability to handle large amounts of power. A new type of transmitter was therefore designed which the writer has called the "trough"

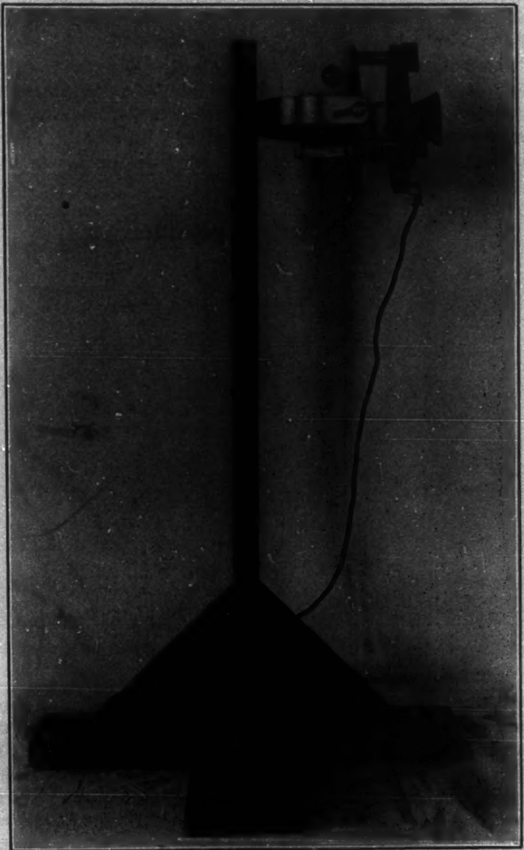

FIG. 24.

transmitter. It consists of a soapstone annulus to which are clamped two plates with platinum iridium electrodes. Through a hole in the center of one plate passes a rod, attached at one end to a diaphragm and at the other to a platinum iridium spade. The two outside electrodes are water-jacketed.

This transmitter requires no adjusting. All that is necessary is to place a teaspoonful of carbon granules in the central space. It is able to carry as much as 15 amperes continuously without the articulation falling off appreciably. It has the advantage that it never packs. The reason for this appears to be that when the carbon on one side heats and expands the electrode is pushed over against the carbon on the other side. These transmitters have handled amounts of energy up to one-half horse power, and under these circumstances give remarkably clear and perfect articulation and may be left in circuit for hours at a time. Fig. 23 shows a modified form with split back.

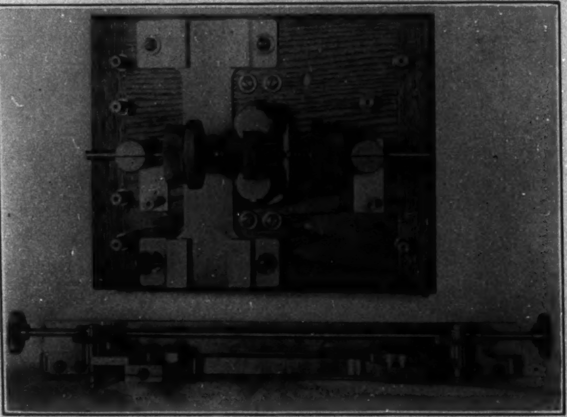

FIG. 25.

Fig. 24 shows a type of condenser transmitter in which the vibration of the diaphragm alters the electrical capacity of the transmitter, thus throwing the circuit in and out of tune or spilling more or less energy through a leakage circuit.

Fig. 25 shows a transmitting relay for strong currents. The only thing noticeable about this is that the telephone magnet is a differential one.

Fig. 26 shows another type of transmitting relay, for amplifying very feeble currents. It will readily be understood that where a person in Albany, for example, wishes to talk to another person on board a ship off New York, the wireless station being located near New York, the volume of the transmission received at New York will not be very strong, and while it may be possible to transmit it without amplification, amplification is advisable.

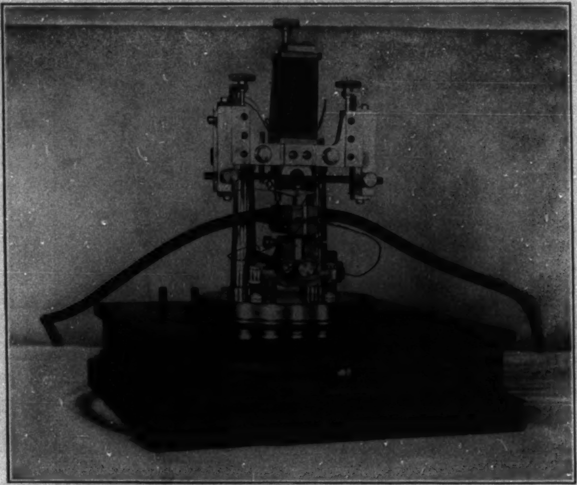

FIG. 26

This receiver is a combination of the differential magnetic relay and the trough transmitter. An amplification of fifteen times can be obtained without loss of distinctness. The side electrodes of the trough are water-jacketed. The successful amplification depends upon the use of strong forces and upon keeping the moment of inertia of the moving parts as small as possible. Amplification may also be obtained by mechanical means but as a rule this method introduces scratching noises which are very objectionable even though comparatively faint.

Other types of transmitters have also been used, such as liquid jet transmitters, Fig. 27 transmitters operating by closing the air-gap in a magnetic circuit, and so changing the inductance of the oscillating circuit, etc.

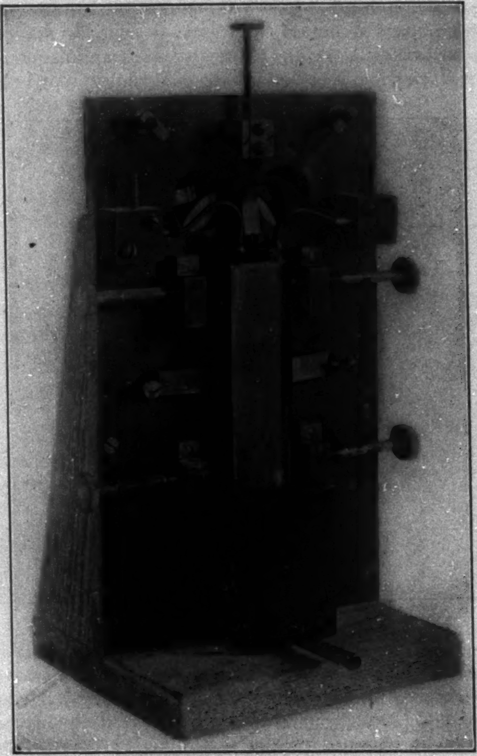

Fig. 27.

Fig. 28 shows a loud-speaking telephone receiver. A small iron disk is placed opposite a nozzle through which air at high pressure is blown. As is well known, this causes the disk to be held close to the nozzle. The telephone magnets alter the position of the disk and thus produce very loud talking.

The transmitting relays are connected in the wire line circuit in the same way as the regular telephone relay, except that in place of being inserted in the middle of the line they are placed in the wireless station and an artificial line is used for balancing. There is no difficulty met with on the wireless side of the apparatus, but on the wire line side there are the well-known difficulties due to unbalancing which have not yet been entirely overcome. For the correction of these difficulties, therefore, we must look to the engineers of the wire telephone companies. At present the difficulties are if anything less than those met with in relaying on wire lines alone.

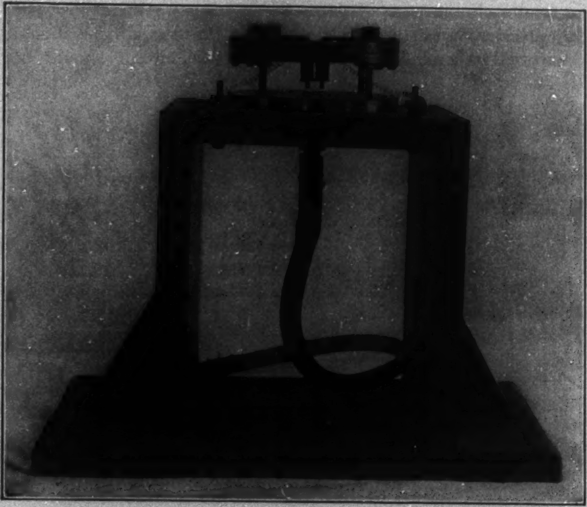

FIG. 28.

3. *Transmitting circuits*. Fig. 29[1] shows a type of arc circuit.

Fig. 30[2] shows a suitable type of connection for use with a high frequency alternator.

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[1] U. S. patents Nos. 706,742, June 6, 1902 and 730,753, April 9, 1903.

[2] U. S. patent No. 706,742, June 6, 1902.

Fig. 31[1] shows a type of circuit for use with the condenser transmitter.

Fig. 32[2] shows a type of circuit in which the modulation is accomplished by changing the inductance of one of the oscillating circuits.

As a matter of fact the transmitter may be placed almost anywhere in the circuit between the arc or dynamo and the antenna, or between the arc or dynamo and ground, or in the transformer circuit, or in shunt to an inductance or capacity, the results obtained in all cases being indistinguishable. The sole criterion of success seems to be that the transmitter should be capable of handling the energy and the circuit should be properly adjusted. Some success has also been attained by placing the transmitter in the field of the dynamo[3] but this method requires very careful designing of the field circuit.

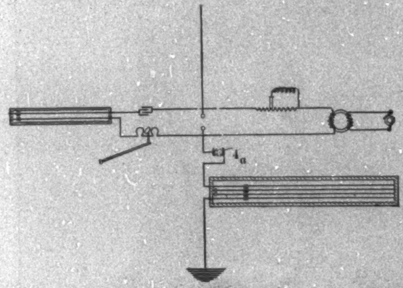

Fig. 29.

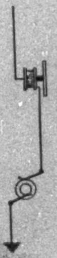

Fig. 30.

4. *Receivers*. The receiver which the writer has found most satisfactory for general purposes is the liquid barretter. Fig. 33 and 34 shows this receiver. It consists of a fine platinum wire, about a ten thousandth of an inch in diameter immersed in nitric acid. Tests made with this receiver show that it responds without apparent loss of efficiency to notes as high as 5000 per second. Some very careful measurements recently made by my assistants, Messrs. Glaubitz and Stein, give the following results:

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[1] U. S. patent No. 706,747, Sept. 28, 1901.
[2] U. S. patent No. 706,747, Sept. 28, 1901.
[3] U. S. patent No. 793,649, March 30, 1905.

| | |
|---|---|
| Voltage of high frequency circuit necessary to produce readable signals, | $15 \times 10^{-5}$ volts. |
| Ohmic resistance of receiver, | 2,500 ohms. |
| Value of high frequency current necessary to produce readable signals, | $6 \times 10^{-5}$ amperes. |
| Electromagnetic wave energy required to produce audible note for period of one second, | $1 \times 10^{-4}$ ergs. |

The telephone used for detecting the signals had a resistance of approximately 1000 ohms. Some measurements were made to determine the change of current in the telephone circuit by using a sensitive galvanometer in series with the telephone but the results obtained were obviously too low, possibly on account of the electrostatic capacity of the turns of the galvanometer with respect to each other. It will be noted that the amount of electromagnetic wave energy necessary to produce a signal is considerably less than that given in a previous note.[1] The difference is possibly to be attributed to improvements in adjustment and operation.

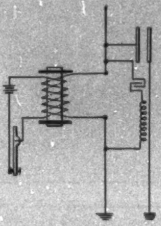
Fig. 31.

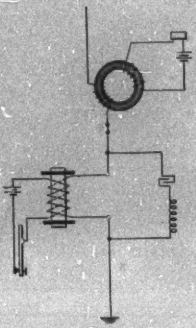
Fig. 32.

The above measurements were taken by shunting the barretter across a piece of straight resistance wire in series with a hot-wire ammeter, to determine the voltage necessary, and by intro-

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[1] *Electrical World and Engineer*, Oct. 31, 1905.

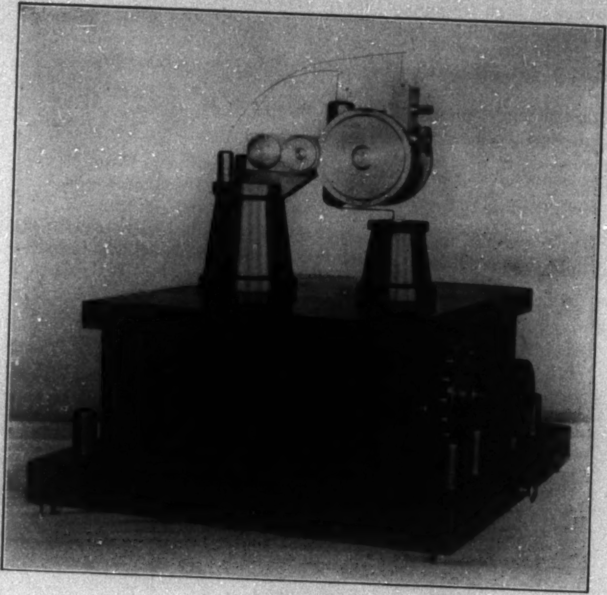

FIG. 33.

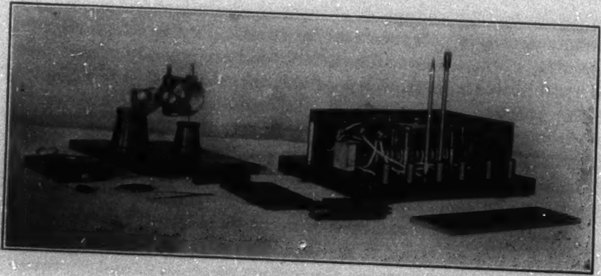

FIG. 34.

ducing resistance in series with the barretter to determine the resistance of the barretter. The figures were also checked in a number of other ways and very concordant results were obtained, so that it is believed they may be relied upon.

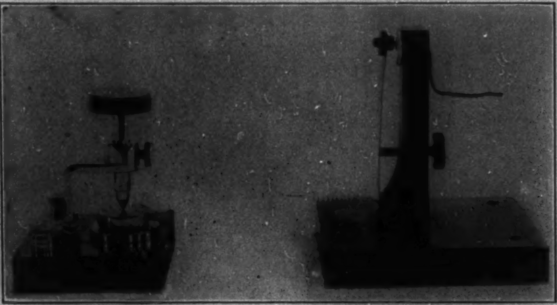

Fig. 36. Fig. 35.

The previously mentioned thermoelectric receivers or rectifiers of Dr. Austin and Mr. Pickard shown in Figs. 35 and 36 and the vacuum tube receivers of Fleming, deForest, and Cooper Hewitt also act very satisfactorily. The fact that the writer has not been able to get as good results from them may be due to greater familiarity with the liquid barretter and heterodyne receiver.

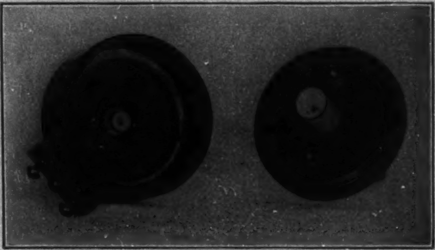

Fig. 37.

Figs. 37, 38, and 39 show forms of heterodyne receiver adapted for use for telephonic work.

5. *Receiver connections.* Where the wireless telephone is operated by first talking into the transmitter and then throwing a switch and listening, the usual wireless telegraphic connections are used. This has been found in practice to be very inconvenient, however, and several methods have therefore been devised for talking and listening simultaneously, which methods can, of course, also be applied to duplex wireless telegraphy. Among these methods may be mentioned the commutator method[1] and the balance method.[2]

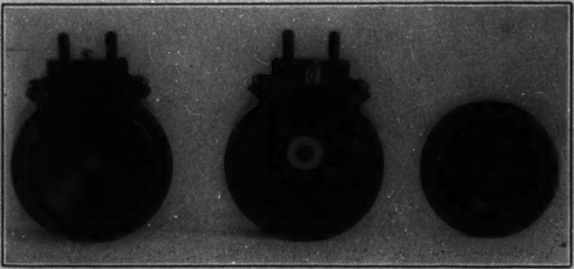

Fig. 38.

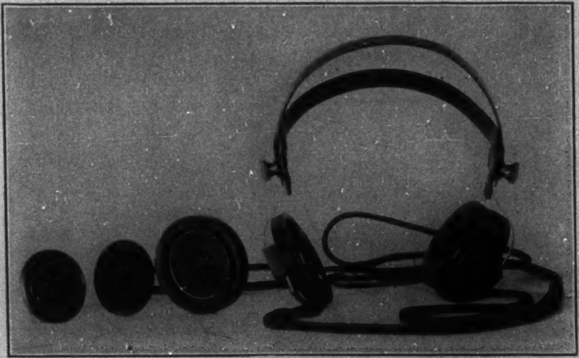

Fig. 39.

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[1] U. S. application, 350,199, Dec. 31, 1906.

[2] U. S. application, 366,528, April 5, 1907.

The former method is fairly well known and consists in rapidly connecting alternately the transmitter and receiver. The balance method consists in using a phantom aerial as shown in Fig. 40, where *P* is a phantom aerial, the circuit having such capacity inductance and resistance as to balance the radiating antenna. The apparatus is shown in Fig. 41.

In order entirely to cut out disturbances in the receiver while sending, an interference preventer, *I. P.*, the elements of which are shown in Figs. 42 and 43, is used in the receiving circuit.

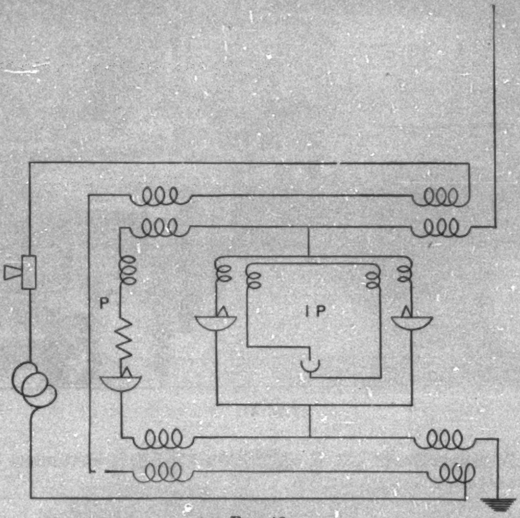

Fig. 40.

It may be here mentioned that balance methods work much better with wireless telephony and telegraphy than with line telephony and telegraphy, for the reason that the radiation resistance of an antenna is absolutely definite and is not affected by the weather, as are line circuits. Consequently, the balance can be made very sharp and once made does not need to be altered.[1] Of course, half the energy is lost but this is a matter of practically no importance, as the cutting down of the strength of a telephonic conversation to one-half is as a rule hardly noticeable, especially where there are no line noises or distortion of the speech through capacity effects.

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[1] This method may, of course, be used for duplex working in wireless telegraphy. As some question has been raised in regard to the capacity of wireless telegraph lines the writer would say that he has received

6. *Receiving station relay.* The receiving station relay is similar to the transmitting relay shown in Fig. 26. The same remarks apply to its use in connection with wire lines as to the transmitting relay.

FIG. 41.

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messages at the rate of 250 words per minute by wireless and is now experimenting with apparatus designed to give 500 words per minute. With duplexing this gives 1,000 words per minute or 60,000 words per hour. The manager of one of the largest cable companies has stated (*London Daily Mail*, Sept. 24, 1907) that all the Trans-Atlantic cables together send 24,000 words per hour. It would appear, therefore, that if capacity alone be considered a single station on each side of the Atlantic can handle more traffic than all the present cables. It should be pointed out, however, that the mere ability to handle the messages is not sufficient and that unless the wireless telegraph companies obtain land facilities equal to those at present enjoyed by the cable companies they cannot handle the traffic as efficiency, *i.e.*, cannot deliver a message from New York to an individual in London and receive a reply in the same time. Fig. 44 shows a Wheatstone transmitter used for the test referred to.

### F. OPERATION

As will be realized from the above, the operation of a wireless telephone system is very simple. The operator merely throws his switch to the position for telephoning and talks into an ordinary transmitter and listens in an ordinary telephone receiver. When the duplex method is used, as is always advisable, the conversation proceeds exactly as over an ordinary telephone line. Fig. 45 shows a phonograph transmitting music and speech wirelessly. Fig. 46 shows talking by relays from a local circuit.

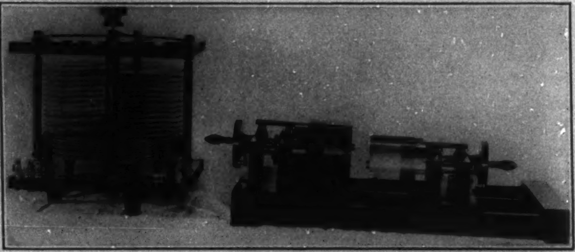

FIG. 42.

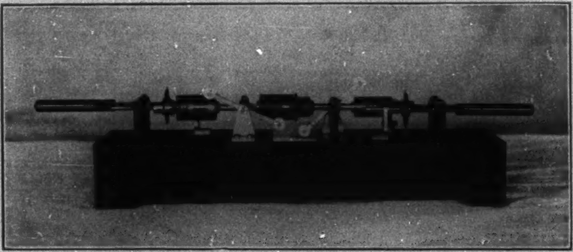

FIG. 43.

I believe I am correct in saying that the transmission by wireless telephone is considerably more distinct than by wire line and that the fine inflections of the voice are brought out much better. This, I presume, is due to the fact that there is no electrostatic capacity to distort the speech, as in the case of wire lines, though I think the effect is also partly due to the absence of telephone induction coils with iron cores. Possibly some of the gentlemen present have witnessed the operation of the wireless telephone transmission between Brant Rock and Plymouth and between Brant Rock and Brooklyn. If so I think they will bear me out in saying that the transmission was clearer than over wire lines.

As a rule, there is absolute silence in the wireless telephone receiver except when talking is going on, though of course the usual noises may be heard if persons are walking across the room, etc. This makes listening in less of a strain than when talking over wire line. Even during severe atmospheric disturbances the talking is not interfered with to any noticeable extent, provided of course that an interference preventer is used.

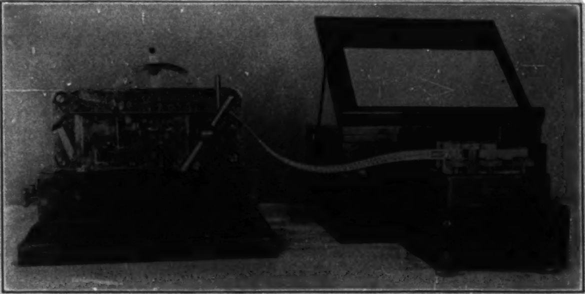

FIG. 44.

A comparative test was made with talking between Brant Rock and Brooklyn by wireless and by wire telephony. The talking over the wire line was done from a long distance station in Brooklyn. The wireless transmission was considerably the better. The fact that the wire line included in its circuits a cable from New York to Brooklyn was of course a disadvantage, but even allowing for this, practice and theory appear to be in agreement to the effect that transmission by wireless telephony over long distances is better than by wire line.

This method should be of especial value to independent telephone companies, which have their local exchanges, but no long distance lines, especially since no franchises or rights of way are necessary.

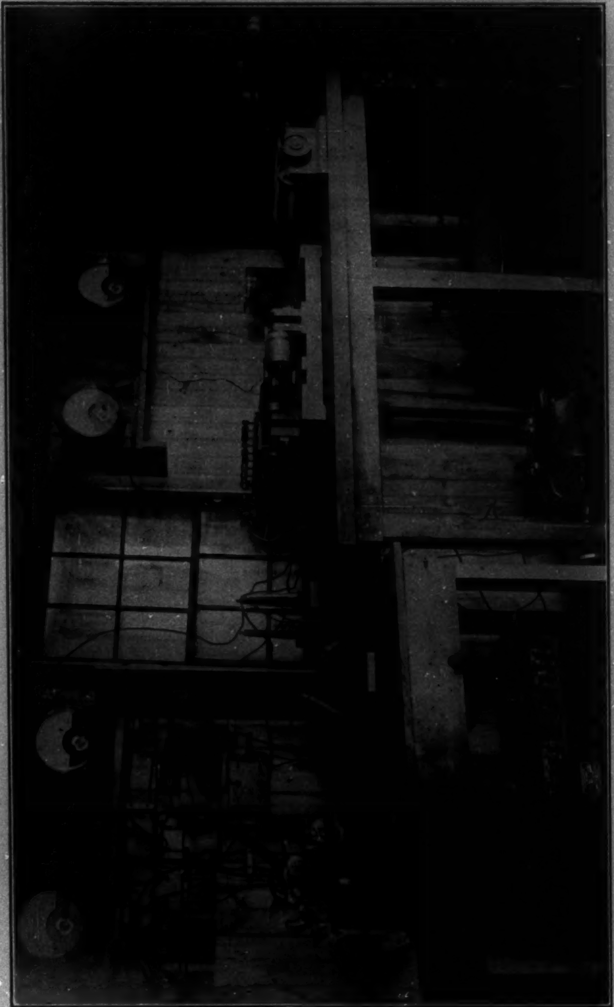

FIG. 45.

## G. Possibilities

A. *Local exchanges*. There is no immediate prospect that wireless telephony will take the place of local exchanges. The difficulty in regard to the number of tunes can be overcome, but the fact remains that high frequency oscillations cannot be transmitted over wire and hence each subscriber must have his own generating station. At the present time no method is known which would be practical if placed in the hands of a subscriber. If such means should be found it would be very convenient to call up directly instead of through an exchange, but as I see it there are no immediate prospects of this.

B. *Long-distance lines*. I believe, however, that there is a field for wireless telephony for long distance lines. The present long distance lines are very expensive to construct and to maintain, and a storm extending over any considerable section of country inflicts considerable loss on the telephone companies. Moreover, the distance of transmission is limited by the electrostatic capacity of the line, as I understand it. Wireless telephony would have the following advantages.

Fig. 46.

1. The initial cost would be very much less than that of wire lines.

2. The maintenance would be practically negligible in comparison.

3. In case of any breakdown, it would be right in the station and not at some unknown point outside on the line.

4. The depreciation would be comparatively small.

5. The number of employees required would be smaller.

6. The transmission is better, and as there is no distortion of the speech, the working distance is, it is believed, considerably greater.

7. The flexibility is greater. With wire lines a telephone company may not be able to give a Boston subscriber a line to New York, while having lines from Boston to Chicago and from Chicago to New York free. Operating wirelessly the wireless circuit normally used for operating between New York and Chicago and between Boston and Chicago could be used to operate from Boston to New York.

8. No right of way need be purchased and franchises it is believed, are not necessary.

It will be noted that I have not mentioned any disadvantages of wireless telephony for long distance work. I presume this is because I am not a telephone engineer. I hope the defects will be discussed by the experts who are familiar with telephone operation and therefore better able to point them out. Before leaving this part of the subject I would say that I think the question of interference has been worked out to such an extent that no serious difficulty need be feared in that direction.

C. *Transmarine Transmission.* Wireless telephony is peculiarly suited for this class of work. Pupin's ingenious and beautiful method has been successful at Lake Constance, Switzerland, I believe, but even assuming that deep-sea cables of this type could be laid and operated successfully, they would nevertheless be very much more expensive than wireless telephone stations. It is believed that wireless telephony will come into extended use for this purpose. Even without further development telephonic communication could be established between Norway or Denmark or Germany or Spain and Great Britain; between Sardinia and Corsica and France and Italy; between France and Algeria, between Australia and Tasmania and New Zealand; between the United States and Cuba and Porto Rico, etc, were it not that it is at present forbidden by law.

As regards telephonic communication between England and America, my measurements show that this should be possible with an expenditure of approximately ten kilowatts and suitably large towers say 600 feet high, or with some of the new forms of antenna. Whether such a transmission would be commercially valuable or not is another matter. Personally I do not see that it would, but when I remember that at the time when the telephone was first being introduced a number of eminent business men decided that the house-to-house printing telegraph would be more of a success commercially than the telephone for the reason that no one would want to do business unless he were able to have a record of the transaction, I must admit that there is a possibility of my being mistaken in this.

D. *Wireless telephony from ship to ship.* Here, of course, wireless telephony occupies a unique position. Wireless telegraphy has the disadvantage that a telegraph operator must be carried. The additional expense is an objection in many cases. The proposition that the captain or mate should also be a telegraph operator has not met with favor. Anybody, however, can operate the wireless telephone and almost every vessel carries an engineer capable of repairing the electrical apparatus in case of accident. The final arrangement will, I believe, (if we can prevent the governments from carrying out their proposed laws, forbidding wireless telephony), be this; that passenger vessels will carry a telegraph operator and use the telephoning apparatus for ordinary work and for telegraphing where it is desired to communicate over long distances. Other vessels will use the telephone alone.

E. *Wireless telephone from ship to local exchange.* This also will, I think, have considerable value, as enabling the captain of a vessel to communicate, by relaying over the wire line, with the owner of the ship, or enabling a passenger on a vessel to communicate with friends on shore.

F. *Range of wireless telephony.* 1. *Atmospheric absorption.* The great obstacle to long distance wireless telegraphy and telephony is atmospheric absorption. For short distances up to 100 miles in the Temperate Zone there is little difference between the strength of the signals at one time of the day and another. As soon as the distance is increased much over 100 miles for the Temperate Zones and 40 or 50 miles for the Tropics the signals at night are very irregular and there is great absorption during the day time. The daylight absorption may be so great that less than a tenth of one per cent. of the energy transmitted gets through. Some nights will be as bad as day-time while on other nights there will be apparently no absorption.

Fig. 47 is a curve showing the strength of the messages transmitted between Brant Rock, Mass., and Machrihanish, Scotland, at night, during January, 1906. Nothing at all was received that month during daytime.

The change in the strength of the signals is very sudden. In working from Brant Rock to Porto Rico, a distance of 1700 miles, the strength of the signals with short wave lengths would fall off to one one-thousandth of their former value during a period of less than fifteen minutes, while the sun was rising.

Early experiments showed that the absorption was greater as the wave length was increased and the effect was at first attributed to absorption in the neighborhood of the sending station, and was thought to increase continuously with the wave length.[1] This fluctuating absorption at one time appeared to place a fundamental obstacle to commercial wireless telegraphy, as telegraph engineers will easily appreciate the impossibility of operating telegraph systems with circuits where the strength of the received signals may fall to one thousandth of its value

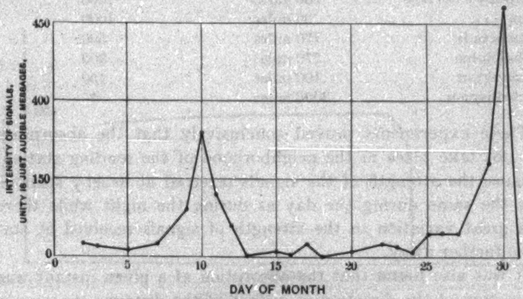

FIG. 47.—Curve showing variation of intensity of transatlantic messages for the month of January, 1906

or rise to a thousand times its value in the course of a few minutes.

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[1] A mathematical explanation of this supposed fact was given by Dr. Fleming "Principles of Electric Waves Telegraphy" pages 617–618, 1906, the following conclusions being reached:

"Accordingly, the chief part of the weakening of the wave by sunlight is done in the neighborhood of the sending antenna, where the magnetic force *H* is greatest, and it is more sensible for long and powerful waves than for short and feeble ones. This agrees with the observations of Mr. Marconi".

It was therefore considered absolutely essential, in order to decide whether long distance wireless telegraphy was commercially possible or not, to investigate this phenomenon fully. As a preliminary the station at Brant Rock sent to four or five other stations at varying distances and comparative readings were taken. The following table shows the general character of the results obtained:

| Station | Distance | Strength of signals received on worst nights (strength of unabsorbed signals being taken as 1000). |
|---|---|---|
| Company's cottage | 200 yards | 1000 |
| Lynn | 30 miles | 1000 |
| Schenectady | 170 miles | 500 |
| Philadelphia | 270 miles | 300 |
| Washington | 400 miles | 150 |
| Machrihanish | 3000 miles | 1 |

These experiments proved conclusively that the absorption did not take place in the neighborhood of the sending station, because the strength of the signals received at nearby stations was the same during the day as during the night while there was great variation in the strength of signals received at stations further away.

It was also found that the absorption at a given instant was a function of the direction as well as of the distance, since on a given night the signals received by stations in one direction would be greatly weakened, while there would be less weakening of the signals received by stations lying in another direction, while a few hours or a few minutes later the reverse would be the case.

This was thought to be connected with the coming weather conditions but before this fact is proved a much larger amount of data must be collected. Through the kindness of the U. S. Weather Bureau I was enabled to obtain a chart of the magnetic variations and on comparison of these with the absorption between the Massachusetts and Scotland stations there appeared to be a quite definite relation, *i.e.*, the greater the absorption the greater the magnetic variation. Here also, however, much more data is needed before arriving at a definite conclusion. The fact that the absorption did not take place in the neighborhood of the sending station having thus been definitely settled the next point to be investigated was whether or not there was any way of overcoming it.

The fact that variations in the absorption occurred with extreme rapidity, the absorption increasing sometimes a hundred fold in a single minute, and at night, when the effect could not be due to the sun directly, seemed to indicate that the body producing the absorption, whatever it was, was not in a state of continuity but was broken up into masses like clouds.[1] This also was in accordance with some experiments made in Brazil in 1905.

From optical theories it is known that where the absorption is produced by conducting masses of a more or less definite size the absorption is to a certain extent selective. The next point in the investigation was, therefore, to determine whether there was any possibility of this being the fact in the case of the absorption of wireless signals.

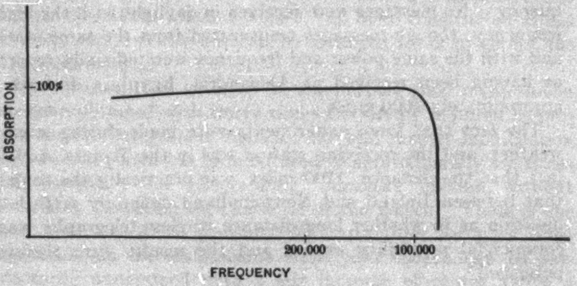

Fig. 47

Comparative tests were therefore made of the absorption at night and during the day between Brant Rock and Washington, with wave lengths varying from a fraction of a mile up to four or five miles. It was found that the absorption did not increase continuously with the wave length but reached a maximum and then fell off with great suddenness.

Fig. 47 shows the general character of the curve, the ordinates referring to the amount of the absorption and the abscissas to the wave frequency.

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[1] *Electrical Review*, May 18, 1906.

It may be noted that the absorption is a maximum at a frequency of about 200,000 per second, nine hundred and ninety nine thousandths (0.999) of the energy being absorbed at this frequency during daylight, while for a frequency of 50,000 the absorption does not appear to be appreciable. Longer experiments, of course, might show some absorption, but in any case it is of a different order from the absorption for the shorter wave lengths.

Experiments were then made between Brant Rock and the West Indies, a distance of 1700 miles, during the spring and summer of 1907. It was found that the results were of the same character, *i.e.* that while there was greater absorption for frequencies of 200,000 there was comparatively little absorption for frequencies in the neighborhood of 80,000 and messages were successfully transmitted in daylight with this latter frequency. No messages were received in daylight with the higher frequency, though messages transmitted from the same station and with the same power and frequency were officially reported as having been received at Alexandria, Egypt, a distance of approximately 4000 miles.

The fact that these experiments were made during summer weather, and the receiving station was in the Tropics, and the fact that the distance, 1700 miles, was practically the same as that between Ireland and Newfoundland definitely settled the question as to whether long distance wireless telegraphy was a commercial possibility or not and the results were therefore published.[1]

Since the publication of the above results transmission has been accomplished by means of these long waves over still greater distances during daylight. Sig. Marconi early in October, 1907, abandoned the short-wave lengths previously used, and adopted one over two units in length, and immediately succeeded in operating between Glace Bay, Nova Scotia, and Clifden, Ireland a distance of more than 2000 miles, the frequency being approximately 70,000. The same messages were received at Brant Rock, Mass., a distance of nearly 3000 miles.

Still more recently Captain Hogg of the "Glacier" has written that during the southward passage of the Pacific fleet he received messages from the station at Brant Rock, Mass., while off Cape Ste. Roque, Brazil, S. A. The frequency used for sending was approximately 80,000, and the messages were received with the very interesting and sensitive silicon receiver invented by Mr. Pickard. This distance of 3000 miles is the greatest yet achieved by wireless transmission during daylight and would indicate that with the use of suitably high towers much longer distances can be reached.

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[1] *The Electrician* (London), July 26, 1907.

2. *Range of wireless telephony and wireless telegraphy compared.* For the same power it is possible to telegraph to a further distance than to telephone. Distinct speech depends upon the presence of harmonics of a frequency as high as 1200 per second. The amplitude of these harmonics is according to some rough experiments made by the writer only about one per cent. of the fundamental frequency. Consequently, with a perfectly modulated transmitter 100 times as much energy would be necessary to telephone a given distance as to telegraph. It fortunately happens, however, that a carbon transmitter and also the circuits in which it is used, can be so constructed as not to modulate perfectly but can be arranged so as to accent the higher harmonics.

With transmitters arranged for the purpose good transmission has been obtained with thirty times the energy required to produce audible telegraphic signals. By still further modification the power required has been reduced to approximately ten times that necessary for telegraphing, curiously enough without noticeably distorting the character of the speech. There is one fact, however, which prevents the ratio from being as large practically as the instruments show, *i.e.*, speech can be satisfactorily understood with a less increase of power above a minimum audibility than telegraphic signals.

The amount of power necessary for wireless telephony may therefore be taken as approximately five to fifteen times that necessary for wireless telegraphy; *i.e.*, under the same circumstances and for the same power the wireless telegraph will carry two to four times as far. The difference in range would be very much greater also but for the curious fact that there is much less falling off with sustained oscillations than with intermittent groups of waves, even though the frequencies are identical.

This fact has been repeatedly determined by sending between Brant Rock and Brooklyn on the same frequency, using in the one case spark produced trains of waves and in the other the high frequency dynamo. The difference in the falling off for the same frequency and energy is very great but further work is necessary before anything very definite can be said about it or the reasons finally determined.

## H. How Wireless Telegraphy has been Throttled by Governmental Action

The question has been asked why, if wireless telegraphy can compete with wire lines and cables, it is not put into operation. This is not an unnatural question. Ninety nine individuals out of a hundred would probably consider that if an inventor had perfected a system of wireless telegraphy or telephony so that it would operate reliably over long distances and would handle messages at a fraction of the cost of the present cables and without interfering with other stations, he would immediately pick out from an atlas half a dozen suitable points for operation, such as from France to Algiers, Italy to Egypt, Great Britain to Germany, New Zealand to Australia, Australia to Hong Kong, or Canada to Great Britain, and immediately commence commercial work, being perhaps delayed a few weeks on account of some slight formalities in connection with obtaining permits. The statement that nothing of the sort could be done would be received with incredulity, especially if it were known that the business men who would benefit by the reduced tolls were strongly desirous of having them put into operation.

This is a very important matter, not because the crushing out of a new system of telegraphy is so very important in itself, but because the prospects are that other branches of the electrical profession may have to face the same situation in the near future and it is, therefore, advisable to show in some detail just what governmental ownership means in its relation to the progress of civilization. I will, therefore, explain fully, but as briefly as possible how commercial wireless telegraphy is hindered by governmental action.

Examination of a chart of the world immediately suggests a number of points as suitable for the installation of wireless communication. For example the following:

1. United States to Cuba.
2. " " " Porto Rico.
3. " " " Jamaica and other West Indian Islands.
4. " " " Bermuda.
5. " " " Newfoundland.
6. " " " Great Britain.
7. " " " France.
8. " " " Azores.

9. Newfoundland “ Great Britain.
10. Great Britain “ Ireland.
11. “ “ “ France.
12. “ “ “ Spain.
13. “ “ “ Germany.
14. “ “ “ Denmark.
15. “ “ “ Norway.
16. France “ Algiers.
17. Italy “ Egypt.
18. New Zealand “ Australia.
19. Australia “ Hong Kong.

The first fact to be noted is that these countries with the exception of Porto Rico are foreign countries and that in practically every one of these, Porto Rico is believed to be the only exception, there are stringent laws in force forbidding the erection of wireless stations without permits. The difficulty of obtaining these permits is shown by the fact that one wireless company within the writer's knowledge has been endeavoring for more than four years to obtain permits in the majority of the above mentioned foreign countries and has so far succeeded in obtaining only one permit and that for direct communication between the United States and Great Britain.

To take a specific illustration. In 1903 an American company was requested to install communication between Bermuda and the United States. The principal industry of Bermuda is the growing of produce of various kinds, which is exported almost entirely to the United States. The only present means of communicating is through Nova Scotia, and in winter especially, owing to the delays on the land lines, the service is often quite insufficient. Permission was asked of the Home Government by the Bermudian incorporators, but without success.

A petition was then signed by virtually every prominent business man in the islands and forwarded to the Home Government. The members of the New York Produce Exchange drew up a petition and forwarded it to the Secretary of State requesting him to use his influence in the matter. The Colonial Office stated in reply that it was favorable to the project but that the matter must be referred to other branches.

The Bermudian business men also sent several representatives to Great Britain to urge personally the granting of the permit. After a lapse of several years a definite reply was received to the effect that the permit would not be granted. The Bermudians then took up the matter through a Canadian company which sent several representatives to interview the authorities in Great Britain but without success. The Lord High Commissioner of Canada, Lord Strathcona, finally was kind enough to interest himself in the matter and personally presented the case before the British authorities.[1] It is hoped by the Canadian company and the Bermudians that the permit will finally be granted, but this specific illustration will explain the difficulty in obtaining permits for operation.

As illustrating a different obstacle the case of Newfoundland may be taken. This is the natural point for establishing communication with Great Britain and the experiments previously referred to as having been made between Massachusetts and the West Indies showed conclusively that there would be absolutely no difficulty in operating commercially and with ease over this distance. On the other hand to operate directly from America is a much more difficult proposition for the reason that, as examination of a great circle chart will show, the whole of Newfoundland and Nova Scotia lies between any point in the United States north of Hatteras, and Great Britain.

If operation in Newfoundland were not forbidden by law half a dozen wireless stations would be at once erected, and the companies would be only too glad to pay into the Newfoundland treasury the ten or twenty thousand dollars per annum to be collected if they were put on the same footing as the cable companies in order to save the cost of the longer transmission. The Newfoundland government a number of years ago granted a monopoly of wireless telegraphy to one company, which company has never erected a transatlantic station in that island. While this monopoly has been very injurious to Newfoundland, on account of the loss of revenue entailed, it has been still more so to the wireless companies and to the public at large, which otherwise would have had cheap transatlantic telegraphy several years ago.

Another very formidable obstacle is the fact that in practically all the foreign countries referred to (and in Porto Rico) land telegraphy is a government monopoly. Consequently, the wireless companies are entirely at the mercy of the government, are barred from collecting their own messages and must pay whatever tolls are fixed by the various governments. This, of course, also operates to prevent rapid service, since instead of communicating directly from Paris to London the messages would have to be sent from Paris by wire line to the French wireless station thence to the English wireless station and thence again by wire to London.

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[1] Since the above was written a communication has been received from the colonial secretary stating that no decision will be given in the matter until the Wireless Company submits a plan for coöperating with the present cable companies (letter of Aug. 6, 1908).

In a number of countries, the cable lines are also owned by their governments which makes them naturally averse to losing the invested capital or to permiting private companies to compete. It would be evident therefore that no matter to what perfection the art of wireless telegraphy is brought, years will elapse and the exercise of a great deal of political influence will be necessary before the public gets the advantages of the cheaper rates.

*Ship communication.* Here again the development of wireless working has been stifled by legislation. Vessel owners were at first rather slow to take up the matter of equipping their ships but after the system had proved its worth in several cases and some of the owners had had to pay large sums for salvage in cases where a wireless installation would have avoided the loss, its value began to be realized. It was at this point that the governments again stepped in with premature and injurious legislation. As a specific illustration, a United States company had arranged with the owners of some two hundred vessels to construct a line of stations from Maine to Texas, to operate with stations installed on the ships. The announcement was made that the administration proposed to recommend to Congress that wireless telegraphy be made a government monopoly.

A representative of the wireless company requested permission to submit some evidence to the effect that such a government monopoly was not necessary and that the various stations could operate without interference. A reply was received from the Administration that " information in regard to the subject was not desired ", and the administration recommended that wireless communication with ships should be made a government monopoly.[1]

It was proposed to carry this out as follows:

1. To establish Navy wireless stations at points along the coast

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[1] Recommendations of the Inter-departmental Board on Wireless Telegraph, 1904 submitted and approved by the Administration.

where wireless stations were needed by the merchant marine.[1-2]

2. To forbid the operation of private stations at these points.[3]

3. The Navy stations are to handle all messages to and from ships free of charge.

4. Wireless companies to be permitted, after obtaining a license from the Department of Commerce and Labor, to erect stations at points where there was no merchant marine business.[4]

The official approval and transmission of these recommendations by the Administration, although they were opposed and never went into effect, terminated, of course, all negotiations with vessel owners, since the owners would naturally not agree to contract for the transmission of their messages with the immediate prospect in view that the Government would transmit them free of charge. At the present time the masts ordered for the proposed line of stations are rotting at various points along the seaboard and the apparatus purchased for installation is deteriorating in storage.

The development of ship communication had just begun to recover from this blow when an International Wireless Telegraph Conference was arranged for by the various governments. In America no opportunity was afforded the wireless companies

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1. *Ibid.* " That the maintenance of a complete coastwise system of wireless telegraphy by the Navy Department is necessary for an efficient and economical management of the fleets of the United States in time of peace and their efficient maneuvering in time of war."

2. *Ibid.* " As fast as the naval wireless telegraph stations are in operation the Navy Department shall receive and transmit through these stations free of charge all wireless messages to and from ships, providing such stations do not come in competition with commercial stations, until such time as Congress may enact the necessary legislation governing this subject". That the statement in regard to competition is disingenuous will be seen from examining the following extra Note 4, since only one station, and that a Navy one would be permitted at points where there was merchant marine business.

3. *Ibid.* " In asking for legislation on this point the board invites attention to the fact that where wireless stations are needed for the merchant marine, as a rule, the navy will also require them. The board believes it to be in the interest not only of governmental but of public economy and efficiency to permit the naval stations to handle the public service, for in the present state of the art but one station is desirable for the public interest in such places. It is admitted that there may be special cases where private stations can serve a useful purpose and the board believes that the Department of Commerce and Labor should have the duty of issuing licenses in such cases under such regulations as will prevent interference with stations necessary to the national defence."

4. *Ibid.*

of presenting the case to the delegates to the Conference, and a very stringent set of regulations was adopted. The Administration transmitted these regulations to the Senate.[1] The ratification of the treaty embodying these regulations was opposed by the Marconi Co., and by the National Electric Signaling Co. The following facts were pointed out:

1. That the proposed regulations virtually amounted to confiscation of the property of the wireless companies; that the working at present was carried on at a loss; that no wireless company was at the present time paying dividends; that the proposed rates would not permit of any return on the capital invested; and that the regulations would so limit the amount of business which it would be possible to transact that it would not pay to keep up the stations.

2. That the inventors in the art of wireless telegraphy had expended large sums of money in developing their systems, and such confiscation was therefore unjust and was thought to be unconstitutional.

3. That the regulations were impracticable in the following respects:

*a.* By requiring ships to use two tunes only[2] all stations were placed, so tc speak, on two-party lines, thereby producing a maximum of interference and preventing any one station working while any other was operating.

*b.* Allowing only five minutes per message and assuming only ten ships each with ten messages to be in the neighborhood of a given seaport, more than eight hours would have to elapse before the last station had transmitted its message. This time is believed to be underestimated, as the regulations provide that each ship before sending its message must call the coastwise station, have a number assigned to it, inform the coast station of its distance, its true bearing in degress, its true course in degrees, its speed in nautical miles, the number of words it has to transmit; must be informed how long it will have to wait, whether the transmission is to be in alternate order or in series, interrupt the sending after each 20 words, send an interrogation mark, wait for repetition of the last word, etc.[3] Hence it would be rather difficult to maintain the average time mentioned. This excessive delay would cut down the traffic to such an extent as to render it impossible for the stations to pay expenses of maintainance, and any telegraphic engineer will appreciate the difficulty of carrying on commercial business under such regulations.[1]

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[1] Senate Document, Sixtieth Congress, first session.

[2] Regulations II and III.

[3] Regulations 19 to 26.

*c.* Placing all vessels on two-party lines introduces all the difficulties of the party line method and loses the only advantage, as it might easily happen that a ship in distress using one frequency might be within range of a number of vessels using the other frequency, but outside of range of any vessel using its own frequency. The obvious and practical method is legally to establish a single tune to be used exclusively for calling and distress signals but not for any other purpose; the transmission of messages to be continued by switching over to other tunes once the call has been received and accepted. In this way a ship in distress can always be sure of calling any vessel within range, while the transmission of messages can be carried on without interference and without one ship having to wait until the other is finished.

4. Its restrictions are of such a character as to prevent the future development of wireless telegraphy. For example.

*a.* The regulation[2] that all stations must carry a licensed wireless telegraph operator capable of receiving at twenty words per minute would prevent the installation of wireless stations on board the majority of ships since only the larger vessels can afford the additional expense of the operator. Many vessels would install wireless telephones which do not require a skilled telegraph operator, if it were not for this regulation.

*b.* The rules forbidding[3] the transmission of telegrams calling for repetition of messages, or for acknowledgement of receipt, or for telegrams to be forwarded, or for telegrams to be delivered by express or by mail, or for the transmission of money-order telegrams or for the transmission of telegrams with answer prepaid, or for the transmission of urgent telegrams are especially restrictive. By forbidding the transmission of telegrams of all the above classes the commercial field of wireless telegraphy is limited to such an extent as to deprive wireless telegraphy of its chief value.

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[1] As a practical illustration of this, on August 12, 1908, the Assistant Secretary of the Navy, on board U.S.S. Dolphin, had to wait two hours before an important message could be transmitted, as the two stations with which he was in range were occupied in sending a long message and the Dolphin was unable to cut in. Had a number of stations working on different times been available, this could not have happened.

[2] Section 6, paragraph III.

[3] Section XXXIII.

5. It expressly forbids the use of a number of the most important developments in wireless telegraphy. For example.

*a.* Section 3 in effect forbids long distance transmission in daylight. This section states that ships must not use wave lengths exceeding 600 meters. It is now well known that daylight absorption is very great for these wave lengths and that much longer wave lengths must be used during daytime. This rule therefore virtually forbids wireless telegraphy during daylight except within a very limited radius, and in case of an explosion or fire on shipboard during daylight the vessel would be unable to summon assistance unless by some fortunate chance another vessel happened to be within the radius limited by the restriction to the short wave length. It also virtually prohibits ships keeping in communication with the shore for more than twelve hours out of twenty-four.

*b.* Section 3 states that the system employed must be a syntonized system, thus forbidding the use of systems such as the heterodyne system which do not depend for selectivity on syntony. This would not be so injurious if it were not for the fact that the present indications are that syntony will in the near future be abandoned as a means of obtaining selectivity.

*c.* The rules of Section 2, 3, and 18 to 26, virtually forbid the use of duplex and multiplex systems. There is no reason why a number of ships should not communicate with the same station simultaneously, but the above rules forbid this by requiring only two wave lengths to be used and the messages to be taken one after the other.

*d.* It is premature. The expression "that an art is in its infancy" is a very hackneyed one but if it can be applied properly to any art it is to wireless telegraphy. The fact that the proposed regulations are unsuitable does not reflect in any way on the ability or conscientiousness of the delegates, though it would seem that it would have been advisable to consult the engineers of the various wireless telegraph companies before drafting the rules. The main difficulty, however, is that no one, no matter what his knowledge of the present state of the art, can foresee the future developments. The question of wave length and daylight absorption is an illustration of this, as is also the question of syntonized circuits. The time has not yet come for any such hard and fixed regulations as thus proposed.

6. It was also pointed out that the public had no rights in

regard to wireless telegraphy, since a patent differs from a franchise in that when the public grants a franchise it gives a right in respect to something which already exists and which it owns, and it therefore has a right to make what stipulation it chooses. In the case of a patent, however, the right is not given in respect to something which the public owns, but in regard to a new creation which exists merely in the mind of the inventor, to be called into being or not at the inventor's will, and therefore a thing in which the public has no right except as it obtains one by stipulation with the inventor. In the case of wireless telegraphy the companies invested their money under the patent law contracts with the various governments, and therefore the inforcement of regulations of the character proposed without the consent of the inventors is a breach of contract.

As a result of the hearing and of representations supporting the position of the wireless companies made by a very eminent electrical engineer the Senate Committee has decided to do nothing for the present in the matter. During the hearing the fact was brought out by the committee that the proposed regulations were passed upon the assumption that interference could not be kept out, and that the U. S. Navy had already made official reports on tests of interference preventers which showed that this was not the fact. On direct question by the Senate Committee the representative of the U. S. Navy present at the hearing freely admitted that it was a fact that interference could be kept out.

Still more recently another set of recommendations has been forwarded by the Administration to the Senate endorsing the recommendation of the Secretary of the Navy that a law should be passed[1] making it an offence punishable by imprisonment for one year of a fine of $2,000 or both for a private station to continue sending when called upon to discontinue by a Navy operator, or to produce interference with a Navy station when the latter is transmitting an official message. This recommendation was not accompanied by any recommendation to the effect that the Navy stations should use any means for keeping out interference. Before the transmission of this recommendation a conference was sought with the Navy officials with a view to drafting a form of regulation which would accomplish the results sought, without placing the wireless companies at the mercy of the Government and without virtually confiscating their property but it was found impossible to obtain a hearing.[1]

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[1] *Congressional Record*, Feb. 14, 1908. Also H. R. bill 17719, 60th Congress, 1st Session.

The following memorandum of a portion of the interview between Secretary Straus of the Department of Commerce and Labor and the representative of the wireless company, asking for a hearing, will be of interest:

**Representative**: "Will you not, Mr. Secretary, be willing to assist us in obtaining a treaty which, while giving the government all it desires in the way of intercommunication between different systems, reservation of wave-lengths for government purposes, etc., will, at the same time, avoid driving the wireless companies into bankruptcy?"

**Secretary Straus**: "The treaty was reported by the experts of the government departments, and we propose to carry it out, as it is the policy of the administration."

**Representative**: "But, Mr. Secretary, these regulations virtually prevent the wireless companies from doing any commercial business. With everybody on one party line, even without the numerous other restrictions, it will not be possible to handle a sufficient number of messages to pay operating expenses, and the companies will necessarily be forced out of business."

**Secretary Straus**: That has nothing to do with this department. If you are injured you should go to the Congress and ask them to reimburse you.

**Representative**: Mr. Secretary, you know that it would be practically impossible to get a bill to reimburse a private company through the Congress. Why should the government crush out a new and important method of communicating which will save the country millions of dollars yearly, when the government will gain nothing by the action. We feel that your department ought to assist us in this matter.

**Secretary Straus**: It has been decided by the administration that the treaty should be approved as it stands.

It will be noted that this conversation took place in the United States, and not in Russia, as might possibly be otherwise inferred. It will appear from this and the experience of others that the original object of the formation of the different government departments has been rather lost sight of in recent years.

It will perhaps be seen that the difficulties in the development of wireless telegraphy have not been wholly of a technical nature and more patience may perhaps in the future be extended to those engaged in the work.

In his book entitled "Public Ownership and the Telephone in Great Britain," Professor H. R. Meyer has treated specifically of the way in which the use of the telephone was opposed in Great Britain, by the English postal authorities with the object of, to quote the Postmaster General, Sir James Ferguson, "Guarding the Post Office monopoly." Professor Meyer shows how out of 77 companies which applied for licenses from 1882 to 1884 only 8 companies succeeded in obtaining permission to work, and how the various authorities prohibited the telephone companies from laying cables in the streets or from opening long-distance pay stations or from building trunk lines in order to force the public to use the telegraph instead of the telephone. It would appear that the same line of policy in a still more aggravated form has been adopted in connection with wireless telegraphy.

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[1] See also appendix.

## CONSIDERATIONS

The subject is, however, one which is bound to concern in the near future other branches of the engineering profession than those now affected and the present appears to be a suitable time for considering the matter more broadly.

Whatever the ultimate object of man's existence may be it is tolerably certain that it is not to occupy his entire mental activity with the question of how many grubs he can secure for food and where he can find a suitable hollow tree in which to spend the night. But whatever we have above this is due solely to the inventor (in which term I include not only the men who discovered how to produce fire and to build houses and steam engines and alternating current motors, and therefore all engineers whether they take out patents or not, but also those who discover how to distribute what is created in such a way as to make it available).

In the state of nature which Tolstoy so greatly lauds and so carefully avoids advance is impossible; all available energy of mind and body is necessarily employed in the problem of maintaining a bare existence. Before we can advance toward our goal, whatever it is, we must first have time and opportunity and a means of maintaining any advance. That we have this time and opportunity is due to the fact that by means of innumerable inventions we are rendered every day less dependent upon the accidents of nature. It would therefore appear, that whatever our ultimate goal may be, the first essential for reaching it is an increased control over the forces of nature.

This increased control can only be obtained through intense effort. When we see a performer at a circus contorting his body into apparently impossible positions we realize the peculiar aptitude and the many years of training which must have been necessary. It is not generally realized, however, that a still more peculiar aptitude and many more years of still more intense training are necessary for those who would do useful work in any branch of mental achievement. We seldom think, in reading a mathematical paper for example, that the author has studied possibly for an average of ten or twelve hours a day for twenty or forty years before achieving sufficient proficiency in his subject to be able to accomplish the work.

To obtain results in a special line therefore a man with special aptitude and training is required. In addition to this there must be the opportunity. Hundreds of thousands, and in many cases millions of dollars are necessary for the development of an important invention. Such sums will not be furnished if there is no prospect of a return. As the success of an invention is always doubtful, the return from a successful invention must be sufficient to cover the losses from the much larger number of failures, for if the average return from one hundred inventions falls below that obtainable from mortgages or other forms of secure investment there will be no incentive.

The following question seem to me to be worthy of consideration:

1. Whether public officials, elected by the people, would consider themselves justified in expending millions of dollars on the development of inventions the success of which was uncertain.

2. Whether the best men to develop such inventions successfully would be found among the Government officials available.

3. Whether development can be expected in an art or industry entirely under Government control or ownership.

4. Whether universal Government control or ownership does not necessarily involve a fixed and non-progressive state as opposed to a state of progress and development.

## APPENDIX

In the United States some additional hindrances on the part of the Government have been met with. For example, in the United States, and in Russia, as well, an inventor has no legal remedy in case the Government appropriates his invention.[1] It might be thought that the inventor could protect himself by suing infringing companies, but this is not so.

The wireless sets originally used by the United States Navy were imported from a country which was not at that time under the Patent Convention, and as they were purchased abroad no action could be taken. The then Secretary of the Navy, Mr. Moody, refused to require the foreign company to appoint a responsible representative in America. It was not until some years later, when, Mr. Morton being Secretary and the matter having been taken up by one of the Senators, this was done, and an injunction was obtained against the representative so appointed.

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[1] Russel *vs.* United States, decided in 1900, 182 U. S. 516.

On further protest the next Secretary of the Navy, Mr. Bonaparte, stated that the patents could not be recognized as they had not been sustained. He was again approached but said that he had decided that he was not bound to respect them as he considered the price too high.[1] He declined, however, to allow the price to be fixed by arbitration, stating that he considered that the price should be fixed with reference to the cost of manufacture solely. It was pointed out that as the cost of labor and material of the particular device concerned amounted to less than a dollar and as a fair manufacturing profit on this would not be more than forty cents, this would afford no means whereby the company would be reimbursed for its expenditure of several hundred thousand dollars in developing the apparatus. To this Secretary Bonaparte replied that that was a matter which concerned the company and that his department had nothing to do with that. The principal infringing companies having been enjoined the Navy and Army began manufacturing the devices themselves in quantities.

Through the influence of one of the Senators the matter was again taken up and it was arranged that the Secretary of the Navy, Mr. Bonaparte, should obtain a legal opinion from the Attorney-General in regard to the matter. This opinion was prepared by one of the Attorney-General's assistants and proved to sustain the claims of the wireless company on every point. Before it was finally transmitted the Secretary of the Navy, Mr. Bonaparte, withdrew his request for an opinion.

The wireless company received a letter[2] from the Navy Department to the effect that by order of the Administration the patents had been turned over to the Navy Department. A written request[3] was forwarded to the Administration, pointing out that the above-mentioned property had been confiscated by the Government without a hearing and asking for a hearing. No reply was received.

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[1] Letter April 19, 1906.

[2] Letter No. 137,244, July 11, 1906.

[3] Letter April 3, 1907.

The above is given as an illustration of the effect of the present law under which an inventor has no legal remedy against the confiscation of his patents by the United States Government. Among other recent instances of confiscation of inventions by the Government may be mentioned those of the Krupp and Armstrong Companies, the San Francisco Dry Dock, etc.

As the situation is not generally understood attention is here called to it. It should be remedied, as it operates very injuriously as regards the Government departments themselves. The Government is deprived of the services of American inventors who either place their talent at the disposal of other countries, as in the case of Hiram Maxim, or turn their attention to other lines. The general result is that the United States Government, instead of leading other nations, is obliged to follow after and copy, though the success of the United States Navy in developing submarine boats is an illustration of what can be accomplished in cases where the inventor has been able to develop his work without confiscation.

In 1906 President Roosevelt's attention was called to the above facts. He was asked if the administration would not introduce a bill to remedy this state of affairs. He replied that the administration had too many bills of its own to look after, but, on further inquiry, stated that if such a bill was introduced the administration would not oppose it.

On the strength of this promise a bill was introduced and unanimously reported, as follows:

HOUSE OF REPRESENTATIVES, 60TH CONGRESS, 1ST SESSION, REPORT No. 184

The Committee on Patents, to whom was referred the bill (H. R. 7653) to amend section 4919 of the Revised Statutes of the United States, to provide additional protection for owners of patents of the United States, and for other purposes, have considered the same, and recommend that the bill do pass with the following amendment:

In line 7, page 1, strike out the words "has been or," and insert the word "hereafter" after the word "shall."

A bill substantially the same as that now reported was passed by the Senate at the last Congress, and favorably reported to the House, but at too late a day in the session to receive consideration.

The object of the bill is to provide for owners of United States patents a remedy for the taking of their property by the United States for public use, when such taking occurs without the license or authority of such owners and without compensation.

In England and in practically all over civilized countries, except Russia and the United States, the Government can not appropriate an invention without paying a fair price for it. A regular tribunal is charged with the duty of determining what is a fair price for the use of an invention appropriated by the Government in case the Government considers the inventor's charge to be excessive. The United States habitually appropriates at its pleasure the patented inventions of its citizens and declines payment therefor. And this notwithstanding the fact that according to the decisions of the Supreme Court a patent of the United States is property within the meaning of the term as used in the Constitution and laws of the United States, and the use of a patented invention by the Government is a taking of private property, which can not be done lawfully without compensation to the owners. (Solomons *v.* United States, 137 U. S., 342, 346; McKeever *v.* United States, 14 Ct. Cls., R., 396; Affirmed S. C. 18 Ct. Cls., R., 745.)

But notwithstanding this right to protection which patentees and other property owners derive from Article V of the Amendments to the Constitution, it has been held by the Supreme Court that the owner of a patent can not restrain its infringement by the United States or an officer or agent of the Government. (Schillinger *v.* United States, 155 U. S., 163 (1894); Russell *v.* United States, 182 U. S., 516 (1900).)

In both of these cases the court held that in the absence of an express contract between the Government and the patentee, or transactions between them from which a contract may be implied, no court of the United States is vested with jurisdiction to entertain a suit or action by a patentee seeking to recover compensation for the use of his invention by the Government.

How next to impossible it would be to make a case of implied contract which would render the Government liable under the court's decision may be inferred from the following statement of the facts appearing in the Russell case just cited. It there appeared that at the Government's invitation Russell exhibited his patented invention to a board of officers appointed by the Secretary of War. The Government announced that it would adopt and use a device embodying his invention. Prior to the adoption and use of the device Russell communicated his patent to the War Department, showing that his patent covered the device and tended the use of his invention to the Government for reasonable compensation. The Government proceeded to use the device without denying Russell's right to compensation, but with the remark that he should seek his remedy by some means other than Executive action. And the Russell case is only a sample case; one of many.

It seems to be necessary and proper to provide for patentees a remedy, such as the passage of this bill will secure, for the invasion of their rights. Without such remedy, patentees are the only persons who are outside the protection of Article V of the Amendments of the Constitution. "Nor shall private property be taken for public use without just compensation."

Without such remedy a patent is not what it purports to be on its face. Many inventors have spent years of their lives and practically bankrupted themselves in developing inventions primarily of use to the Government, only to find in the end, after their property has been seized by the Government, that they have no legal means of redress, and that the governmental Departments will not recognize the decisions of the courts.

Without such remedy there is a ridiculous discrimination between inventors. The inventor of a children's game or of a new brand of chewing gum is protected by the courts. But the inventor of a device which may save the nation from an humiliating defeat in time of war, or reduce the cost of carrying the mails, or reduce the number of shipwrecks on the coast, is afforded no protection; the governmental Departments have the power to confiscate his property and habitually exercise that power. It may be a new type of breech mechanism, or a dry dock, or a method of communicating with ships at sea; if the invention is valuable the Government can and does seize it, though the inventor may have spent years of his life and bankrupted himself and his friends in developing it.

It may be conceded that the Government ought to have the right to appropriate any invention necessary or convenient for natural defense or for beneficent public use, and that, too, without previous arrangement or negotiation with the owner. Nevertheless, the appropriation having been made it would seem that justice to the citizen demands that in due time he should receive fair compensation for his property.

The claim is made by some that the Government, being the grantor of the patent, ought to have the right to use without compensation such inventions as are necessary for its purposes.

One answer to this is that there is no such limitation or reservation in the law governing the granting of patents; and another answer is that if that were the law there would be no time, brains, or money spent by anyone in inventing those things for which there would be no remuneration.

But it is useless to multiply reasons to justify the passage of the bill. The one fundamental reason already assigned is unanswerable—that no American citizen's property can be appropriated for public use by the Government or by anyone else without compensation being made therefor.

The amendment proposed, by striking out the words " has been or " and the use of the word " hereafter," in line 7, page 1, is deemed advisable, that there may be no question arising upon statutory construction that the law is not retroactive in its effect, but will apply only to future appropriations of patents by the Government.

It passed the House of Representatives by a large majority, the leaders of both the Republican and Democratic parties speaking in favor of it. It passed in the Senate unanimously. It did not become a law, however, as President Roosevelt declined to sign it, though its signature was strongly recommended by Secretary Taft, Senator Knox, and others. No reason was given by President Roosevelt for declining to sign the bill, but it is understood that his action was due to the fact that the ratification of the proposed wireless treaty had been opposed by one of those interested in the passage of this bill.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N.J., June 29, 1908.*

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# THE MEASUREMENT OF ROTARY SPEEDS OF DYNAMO MACHINES BY THE STROBOSCOPIC FORK

BY A. E. KENNELLY AND S. E. WHITING

It is the object of this paper to call attention to what has already been accomplished by others in the direction of measuring rotary speeds with the stroboscopic fork, and also to a certain new modification of the principle which has been developed by the authors.

*Definition.* A stroboscopic fork consists essentially of a tuning fork, such as is shown in Fig. 1, carrying at its extremities a pair of thin strips, or flat shutters, in the plane of vibration. A narrow slit is cut in each shutter parallel to the fork's length. These slits lie opposite to each other when the fork is at rest, so as to permit an observer to see through both slits in this condition. When the fork is thrown into free vibration, the line of vision is interrupted by the vibrating shutters, except during a very brief interval once in each alternation, or twice in each complete cycle, of the fork's vibration, when the slits pass each other, moving rapidly in opposite directions. If then the fork makes say 60 alternations per second, corresponding to a vibration frequency of 30~, there will be 60 brief visual stimuli per second admitted to the retina of the observer's eye. If the object under inspection through the shutters is rotating in such a manner that consecutive retinal images are similar and symmetrical, the picture apprehended by the observer will be continuous and stationary; that is, the object will appear to stand still. Moreover, a certain cyclic range of departure from strict uniformity in the successive images formed on the retina will give an impression of a continuously rotating picture.

If the appearance presented by a rotating object is stationary, when viewed through a stroboscopic fork, we know that the speed of the object's rotation is constant, and also that it bears some simple numerical relation to the speed of vibration of the fork. Since the rate of a tuning fork's vibration is remarkably constant, is nearly independent of temperature changes, and can be determined once for all with great precision, the speed of rotation under inspection becomes known with a like degree of precision.

*Brief historical outline.* The stroboscopic fork has been known and used by physicists for some time. It has been used, for example, in the Lorenz method of determining the absolute value of the ohm.[1] In the Lorenz apparatus, a stroboscopic fork has been used to measure the speed of rotation of a small driving motor to within one one-hundredth of one per cent. Although stroboscopic methods have been used to some extent in engineering tests, the stroboscopic fork has only recently been employed for measuring the speeds of dynamo machinery. The stroboscopic fork was described in this connection in a paper on "Stroboscopy", by Dr. Charles V. Drysdale, read at the Optical Society London in 1905, and shortly afterwards reprinted.[2] Figs, 1, 2 and 3 are taken from that paper. The tuning fork he employed was like that in Fig. 1, held in the observer's hand and excited into vibration at suitable intervals, by mechanical impulses, such as a light blow on the knee. The vibration frequency of the fork was 50 cycles per second, or 6000 peeps per minute. The target shown in Fig. 2 was mounted concentrically on one end of the rotating shaft whose speed was required to be measured. At every 100 revolutions per minute of the shaft, (*i.e.* 100, 200, 300, etc., rev. per min.), the serrated edge pattern of this rotating target would appear stationary. Moreover, at certain speeds, the square, the pentagon, and the hexagon would severally appear stationary. Fig. 3 represents

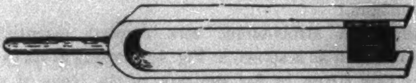

FIG. 1—Stroboscopic fork

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[1] "Absolute Measurements in Electricity and Magnetism", by A. Gray, London, 1893, Vol. II, page 594.

[2] "The Optician and Photographic Trades Review", Dec. 8 and 15, 1905.

the retardation speed-time curve of an unloaded motor, after switching off, obtained by stroboscopic-fork observations.

A paper on "Accurate Speed, Frequency and Acceleration Measurements," by Dr. Drysdale, appeared in the "*Electrical Review*," of London, for September 7 and 14, 1906. Figs. 4, 5, and 6 are taken from that paper, which describes an electrically driven fork, as seen in Fig. 4, the details being given by Dr. Drysdale in Fig. 7. The standard vibration frequency is 50 cycles per second, and the target described was the same as in the previous paper, Fig. 2. Fig. 5 illustrates the device for calibrating the fork. This fork, *F*, is mounted in front of a small shunt motor that can be accurately controlled in speed with the aid of the hand rheostat, *R*. The motor is driven in synchronous relation with the fork, as evidenced to the observer by the standstill of the pattern on the target, *T*. The revolution-counter, *C*, geared with the motor shaft, is then allowed to register for say ten minutes by a stop-watch; so that the record of the counter, *C*, during that time enables the uniform speed of the motor, and of the fork, to be determined closely.

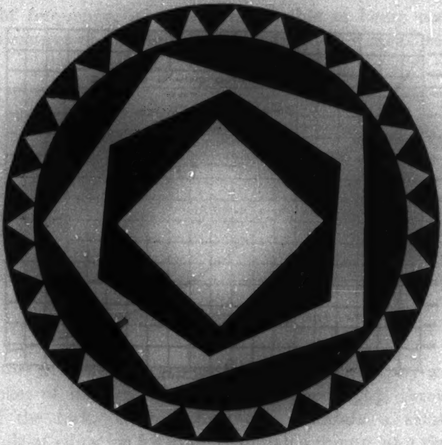

FIG. 2—Stroboscopic target

For rotary speeds intermediate between those at which the target patterns appear to stand still, the simple stroboscopic fork of Figs. 1, 5 and 7 can only serve to measure speeds indirectly, by enabling the observer to count the apparent revolutions of the target image during say one minute by the watch. For example, if the motor's speed was say 1200 rev. per min., the target, viewed through the fork, would appear stationary; but if the speed increased to 1220 rev. per min., the target would appear to rotate 20 times per minute in the direction of motion. It is desirable for many purposes, however, to bring the picture of the target to a standstill at any or all steady speeds within the ordinary range. Dr. Drysdale effected this in the manner indicated in Fig. 6. The conical roller, *R*, was driven by a sort of direct-current synchronous motor, *M*, which in its turn was operated by current impulses from the electrically driven standard fork. A thin disc, *D*, with radial slots, runs on the surface of the conical roller; so that by moving the disc from the smaller to the larger end of the cone, the speed of the disc's rotation could be increased and regulated very definitely. In this way the number of peeps per minute can be brought into synchronous relation with the number of revolutions per minute of a target on a rotating shaft under observation, and the coincidence is rendered manifest by the picture of the target pattern becoming stationary, when viewed through the rotating slots.

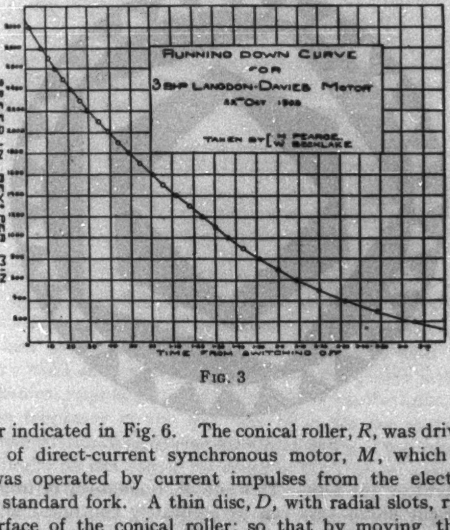

FIG. 3

Dr. Drysdale's paper set forth the advantageous application of the stroboscopic fork to the measurements of acceleration, retardation, uniformity of speed, frequency and slip.

The stroboscopic fork has also been employed in the United States by Dr. Northrup for adjustably varying and controlling the speed of a small alternating-current generator or converter.

The convenience and precision of the method employed by Dr. Drysdale was observed by one of the writers of this paper on the occasion of a visit to the Northampton Institute, London, in 1907. The writers believe that his method only requires to be more generally known in order to be used extensively. A simple stroboscopic fork, such as is shown in Fig. 1, selected for the right frequency, is sometimes capable of being used as a speed measurer of an engine, or as a frequency measurer of an alternator, without even the use of a special target, by watching the spokes of its flywheel, in a fairly good light, through the slits of the fork. Such a fork can maintain a satisfactory amplitude of vibration for more than half a minute at a time after being set in vibration, is very portable, simple, and not easily deranged, under ordinary care.

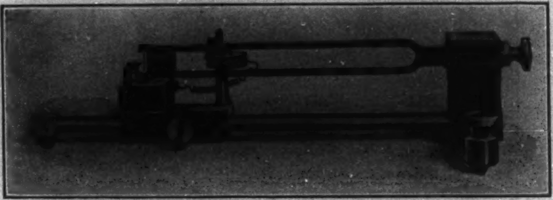

FIG. 4—Electrically driven tuning fork, with slits

*New modification of the stroboscopic fork.* The great advantage of the stroboscopic fork is that when it is vibrating in synchronous relation with the rotating target, the latter appears stationary, and very small changes in speed may then be readily detected. For example, if the target on the rotating shaft makes 1200 rev. per min., and appears stationary through the fork slits, an increase or diminution of one rev. per min., or one-twelfth of one per cent. in the speed, would cause the picture to rotate once per minute forwards or backwards respectively, a rate of rotation that is readily capable of being noted by the observer. The difficulty is that, in practice, the speed to be measured is seldom in exact synchronous relation with the fork. If the target has such a pattern that its picture becomes stationary at each and every 100 revolutions per minute, the speed to be measured may lie anywhere between the century limits, and the fork is unable to make the picture stationary. As already mentioned, Dr. Drysdale has met this difficulty by the use of a conical roller with stroboscopic disc, and this may be a satisfactory solution of the problem for use in the laboratory with a stationary apparatus; but the conical roller device is not portable.

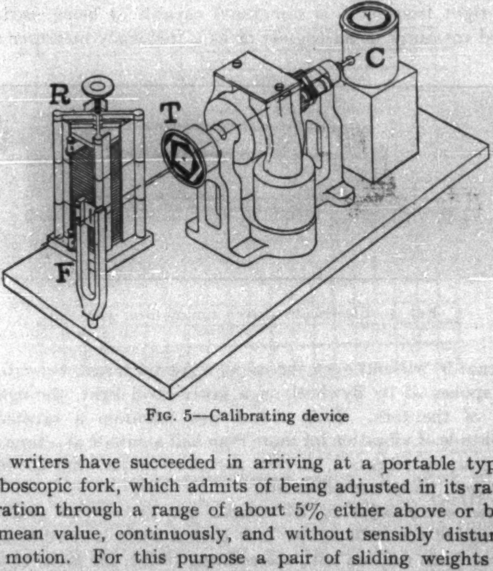

FIG. 5—Calibrating device

The writers have succeeded in arriving at a portable type of stroboscopic fork, which admits of being adjusted in its rate of vibration through a range of about 5% either above or below its mean value, continuously, and without sensibly disturbing the motion. For this purpose a pair of sliding weights grip the sides of the fork friction tight, and can be moved gradually from one position to another within a range of about 7½ inches (19 cm.) by a pair of strings passing over guide-pulleys, and normally slack.

The instrument is shown in perspective in Fig. 8. Its details, in plan, elevation, and end views appear in Fig. 9.

*Details of construction.* Referring to Fig. 9, the fork $A$ is made of a strap of vulcan tool steel 36.7 in. (93.0 cm.) long, 1 in. (2.54 cm.) wide, and $\frac{3}{16}$ in. (0.475 cm.) thick, weighing, without attachments, 1.925 lb. (873 gm.). The over-all length of the fork along its midplane is 18 in. (45.8 cm.). The reason for using so long a fork was to produce a low-frequency vibration, or a fork speed comparable with the speeds ordinarily met with in rotating machinery.

The fork is mounted on a base-plate of cast aluminum by an aluminum clamp with a steel screw $\frac{1}{4}$ in. (0.64 cm.) in diameter. The free ends of the fork carry a pair of thin sheet-steel shutters with slits 0.59 in. (1.5 cm.) long and 0.008 in. (0.2 mm.) wide. There are small brass screw adjustments for bringing these slits accurately in conjunction when the fork is at rest, and there are also small brass screw clamps, with copper washers, for clamping the shutters in this position. The fork can be tuned to the required normal frequency by small brass weights clamped on pins set into the free ends of the prongs, near $C$.

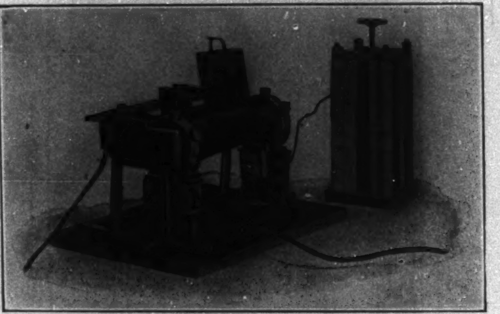

FIG. 6--Roller stroboscope

The sliders, $B$, are rectangular pieces of cast iron, milled out to travel smoothly over the fork, and closed by brass plates on the outer sides of the prongs. The brass covers are provided with recesses $\frac{1}{8}$ in. ($\frac{1}{3}$ cm.) deep, into which fit bent strips of clock-spring, 1 in. (2.5 cm.) long and $\frac{3}{8}$ in. (1 cm.) wide. These springs rest with their two ends pressing against the outer surfaces of the prongs, and prevent the sliders from moving when the

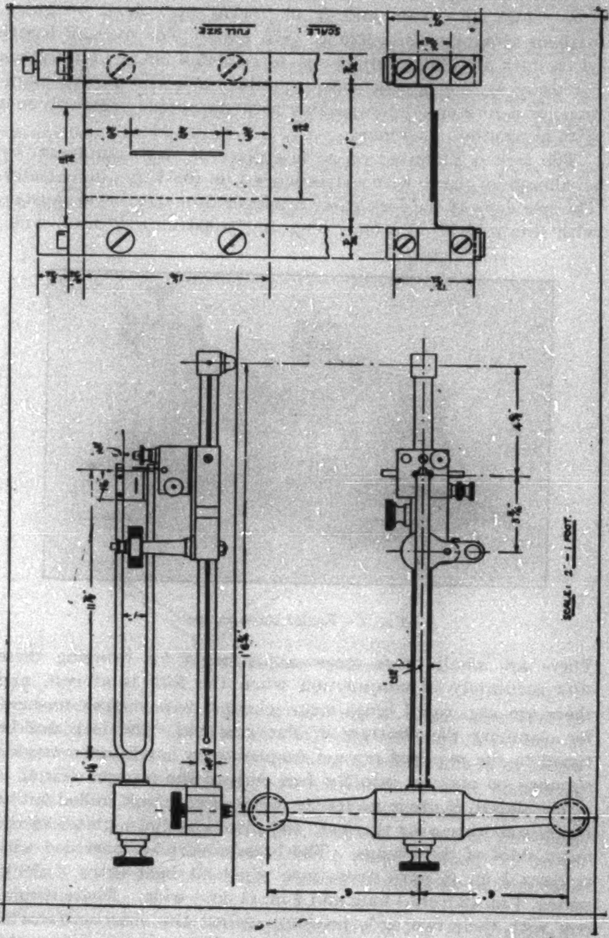
SCALE: FULL SIZE
SCALE: 2" = 1 FOOT

FIG. 7—Details of Drysdale fork

fork is held upright. At the same time the sliders do not grip the prongs so tightly but that they are readily slid along by strings which are fastened to them. These strings pass over guide-pulleys of aluminum, some on the base and others on the prongs, and are clamped under screws carried by the aluminum wheels *J*, near the apex of the fork. The strings lie normally slack, and vibrate with the fork. Tension is applied in either direction by the hand of the observer on one of the wheels *J*. The wheels are clamped on a common shaft in such a manner that they exert equal and symmetrical tensions on the two strings and pull the sliders along evenly. The sliders carry pointers that move over graduated scales, from which the speed of the fork can be read directly.

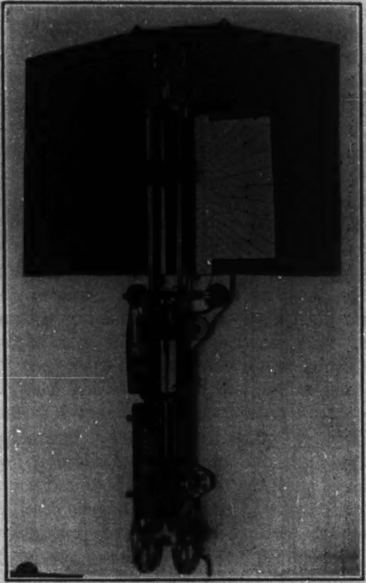

FIG. 8—Perspective view of variable-frequency fork

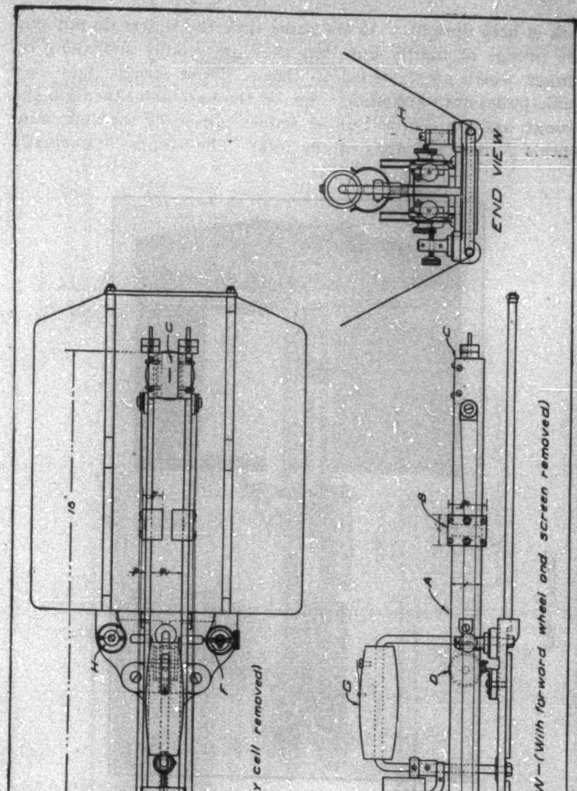
PLAN VIEW—(With dry cell removed)
SIDE VIEW—(With forward wheel and screen removed)
END VIEW
18"
A
B
C
D
E
F
G
H
J

FIG. 9—Details of variable-frequency fork

The fork is driven by the electromagnet, *D*, held between the prongs in a brass sleeve, mounted on an adjustable aluminum sole-plate. The electromagnet spool carries 15 layers, each of 35 turns of enameled copper wire 0.0165 in. (0.42 mm.) enameled to 0.018 in. (0.456 mm.), and offering a resistance of about 3.25 ohms. There is a very light steel spring fastened to each prong near the electromagnet, and one of these springs is used to open and close the circuit by a platinum-tipped contact, vibrating against the tip of an adjustable milled-head brass screw, *F*, set in an insulated aluminum split post. The resilience of the contact spring must have no appreciable effect on the speed of the fork, as is easily tested by watching a synchronously rotating target while turning the axis of the fork slowly by the handle. In order to suppress sparking at the vibrating contacts, a spool *H*, carrying a few feet of insulated german-silver wire, of about 70 ohms resistance, is connected permanently in shunt to the contacts. Current is supplied to the electromagnet from a single dry cell of standard type, having an electromotive force of 1.45 volts, and an internal resistance of about one-third ohm. The average current strength used in operating the fork is about 0.15 ampere. The dry cell, *E*, is held in spring clips, in such a manner that inserting the cell into the clips automatically inserts the cell into the circuit, or effects the necessary electric connections. The amplitude of vibration of the prongs of the fork is about ⅛ in. (3.2 mm.) at the slits, on each side of the zero position, or position of rest, which produces a maximum cyclic velocity of about 1 foot (30 cm.) per second at the normal speed of the fork. Since the slits pass each other travelling in opposite directions their relative velocity is about 2 feet (60 cm.) per second, and the duration of each peep through the slits will be one three-thousandth second, or one one-hundred-eighty-thousandth minute. A target rotating at 1800 rev. per min. will only move through one one-hundredth of a revolution during each peep, and since the pitch of the teeth on the outer edge of the target is one-eighteenth of revolution, the blurring of the visual image, due to the motion during the intervals of vision, will only be about one-sixth of the pitch. The blurring is not troublesome if the motion during each peep is distinctly less than one-half of the pitch in the pattern under examination. The higher the speed of rotation, therefore, the greater must be the speed of the slits, either by increase of vibration amplitude or increase of frequency, and the narrower must be the slits, other things being equal. The same result will be produced, however, at high steam-turbine speeds, by using targets of smaller number of teeth in the pattern, so as to increase the pitch.

The instrument is held by the handle, *G*. The handle carries a small contact key, which is closed by the hand grasp, for automatically interrupting the voltaic circuit when the apparatus is laid aside. The weight of the instrument complete as seen in Figs. 8 and 9 is less than 6 lb. (2.65 kg.).

A pair of brass rods support aluminum sheets that shield the observer's eye from extraneous light when looking through the slits. The sheets also carry the scales for reading off the speed of the fork, and they fold over the prongs so as to cover the slits when the fork is out of service.

*Process of observing.* In order to make a measurement, it is necessary to fasten the target concentrically upon an end of the rotating shaft whose speed is required to be ascertained. Cement, or soft sealing wax, will serve for a dynamo- or motor-shaft. A shaft that runs warm, and has an oily surface, is hard to apply cement upon. In such cases, a metallic spring clip has been used. When neither end of the shaft projects from a bearing, it is difficult to fasten the target on. Sometimes, however, the spokes of the wheels on the shaft will serve as a target. If not, it may be necessary to mount the target on a light auxiliary shaft in bearings, and drive a pulley on the same from the shaft which is without projecting ends, by an endless tape belt, so as to bring the speed of the target into definite relation to the speed of the shaft under test.

The target should receive good daylight illumination. In the absence of such natural illumination, excellent results can be secured from a single 16 candle-power lamp and opaque reflecting shade, supported near to the target, so as to throw on its surface an illumination of about 25 foot-candles (300 meter-hefners).

The observer takes a convenient position facing the revolving target, holds the fork in his left hand, with the prongs vertical, and looks through the slits. If he is sitting, he rests the aluminum foot of the baseplate on his knee. He then moves the wheels with his right hand, until one of the patterns on the target, preferably the external one, comes to a standstill. He then reads the speed from the scale.

*Target.* After many experiments on different sizes, colors and patterns of target, the writers have selected in preference that shown in Fig. 10, bearing white markings on a black ground. Its diameter is 9.5 in. (24.2 cm.). It is made, with advantage, on paper, with the aid of a stencil, and pasted on a backing disc of cardboard, pasteboard, or sheet metal, for mounting on the rotating shaft. It will be seen that it differs only in minor details from the target indicated in Dr. Drysdale's earlier paper, (Fig. 2).

If the pattern on a rotating target has $a$ positions of symmetry per revolution, and makes $n$ revolutions per unit of time, and if the speed of the fork's vibration is such that it provides $p$ peeps per unit of time, then the pattern will appear stationary through the fork when $(a\, n)$ and $p$ are in integral numerical relation. Ordinarily, $(a\, n)$ is greater than $p$; so that standstill occurs in the picture when $\frac{a\, n}{p}$ is any integer. For instance, either a pentagon or a five-pointed star, rotating about its center of figure, has 5 positions of symmetry per revolution. If the

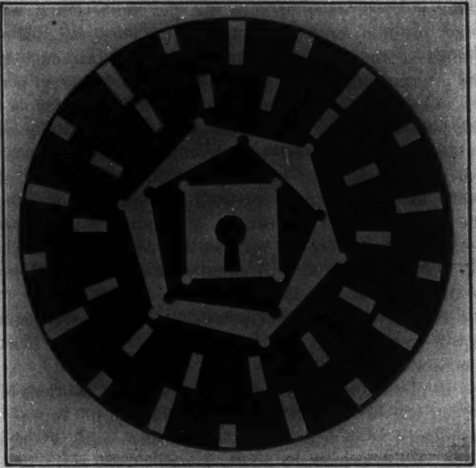

FIG. 10—Target for use with variable-frequency fork

fork gives $p = 1800$ peeps per minute, and the speed of rotation is say just $n = 1080$ revs. per min., then $\frac{a\,n}{p} = \frac{5400}{1800} = 3$, an exact integer, and the picture will appear stationary. Moreover, the pentagon will be moving through three positions of symmetry, or 216°, between successive peeps.

The target of Fig. 10 contains a square, a pentagon, a hexagon, a 14-point star, and an 18-point star. The fork has a mean speed giving 1800 peeps per minute. The square, having 4 positions of symmetry, will appear stationary at 450, 900, 1350, 1800, 2250, 2700, 3150, or 3600 rev. per min., that is, at every 450 rev. per min. or quarter of synchronous speed. Moreover, the image of the square will appear doubled, although fainter, at the intermediate speeds of 225, 675, 1125, etc., rev. per min.; that is at every 225 rev. per min., or eighth of synchronous speed.

The pentagon, with 5 positions of symmetry per revolution, will stand still at every 360 rev. per min., or fifth of synchronous speed. It also appears stationary, doubled but less plainly, at every 180 rev. per min., or tenth of synchronous speed.

The hexagon, with 6 positions of symmetry per revolution, will stand still at every 300 rev. per min., or sixth of synchronous speed. It doubles and will stand still at every 150 rev. per min., or twelfth of synchronous speed.

The 14-point star, with 14 positions of symmetry per revolution, will stand still at every 128.6 rev. per min., or fourteenth of synchronous speed.

The 18-point star, or external circle, with 18 positions of symmetry per revolution, will stand still at every 100 rev. per min., or eighteenth of synchronous speed. Since nine of the points are long, and intermediate points are short, the series of 18 will be stationary and clear for even hundreds, and stationary but blurred on the inner edge, for odd hundreds of rev. per min.

The reason for selecting the above described particular set of target patterns is that it includes the following series of integral values for $a$:

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, and 18. In other words, standstill of some pattern will be produced with the normal fork speed at any half, third, fourth, fifth, sixth, seventh, eighth, ninth, tenth, twelfth, fourteenth, or eighteenth of synchronous speed. In addition to this, the speed of the fork can be varied adjustably within a range of 5% above or 5% below normal. This is sure to bring some pattern to standstill at any except very low speeds of rotation. By means of a graphic chart, and a little examination of the pattern, the speed of rotation can be read off directly from the pointers on the sliders. A displacement of 1 mm. (0.0394 in.) corresponds, on the average, to a change in fork speed of about 1.25 peeps per minute, or less than one-tenth of one per cent.

The scale of speed variation with slider displacement is not evenly graduated. The successive intervals correspond to an equation of the second degree. The distance that must be moved for a change of one revolution per minute is about 20% greater when the sliders are approaching their limit near the middle of the prongs, than near their limit towards the end of the prongs. This means that the scale must be prepared from a suitable number of calibrating observations. The simplest way to calibrate the scale is to keep the speed of the rotating target constant, by the control of an observer with an auxiliary fork, and to count the number of revolutions per minute of the image through the calibrated fork, with a stop watch, as the sliders are shifted from point to point along the scale, say 1 cm. at a time.

*Applications of the instrument.* As pointed out in Dr. Drysdale's papers, the stroboscopic fork is a very convenient instrument for measuring speeds with precision, and particularly for measuring small variations of speed. The device is, in effect, a speed-variation microscope. The instrument is useless when the speed is rapidly varying through a wide range in an irregular manner, except that it gives in such cases ample qualitative evidence of such irregularity. Cyclic variations of speed, as in the hunting of a synchronous motor, if not too rapid, can be measured by observing the angle of oscillation of the target pattern. Variations in the frequency of an alternator, or of slip in a motor, can be observed with ease. There is something fascinating in the pictures presented by the instrument, which are very striking when observed for the first time.

*Limits of accuracy in the use of the apparatus.* The degree of accuracy of the simple stroboscopic fork is remarkably high, and of the order of one part in ten thousand. The variation of fork speed with temperature is about 0.01 per cent. per degree cent. according to measurements reported.[3] In the fork with adjustable sliders described in this paper, the degree of precision in speed is reduced to some extent, owing to errors in the parallel movement of the two sliders, and to errors in reading off their position along the scale. Nevertheless, the degree of accuracy remaining is much greater than is ordinarily needed in engineering measurements. Moreover, the degree of accuracy with which *slow* variations in speed can be observed is as high in the fork with adjustable sliders, as in the simple fixed fork. At 1800 rev. per min., it is easily 1 part in 1800, and it increases in direct proportion with the speed.*

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[3] Electrical Review article, Sept. 1906.

So far as the writers are aware, there is no patent on the method of measuring speeds here described, and it is free to all users.

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*The writers desire to express their indebtedness to Dr. Drysdale, not only for the matters appearing in his papers, but also for illustrations and suggestions directly received from him.

## DISCUSSION ON "THE MEASUREMENT OF ROTARY SPEEDS OF DYNAMO MACHINES BY THE STROBOSCOPIC FORK."

### ATLANTIC CITY, N. J., JUNE 29, 1908

**J. B. Taylor:** The stroboscopic disc illuminated by an alternating-current arc or incandescent lamp has been used for a number of years to determine the speed of induction motors, synchronous machinery, and other pieces of apparatus. This method of obtaining intermittent illumination is much simpler than by means of the fork described in this paper, and for some purposes gives the desired information with greater accuracy.

The distinction between the two methods is that the fork gives very accurate speed determinations, while the illumination by an alternating-current source of light gives even more accurate relative speeds of apparatus and frequency in alternating-current systems. In operating and testing alternating-current machinery the electrical engineer is more often interested in the relative speeds of generator and motor than in the exact determination of speed referred to the clock. For example, in testing an induction motor it may be desirable to know whether the slip under a given load is, say, 2 or 2.1%, while it is immaterial to know whether the motor is actually running at say 1800 or 1795 rev. per min. For this test the alternating-current illumination gives the slip directly, while the fork would require simultaneous observations on the motor, the generator or the synchronous motor.

When studying pulsation of synchronous machinery or angular lag of synchronous motors, synchronous converters, etc., with variable loads, excitations, and reactances in circuit, the alternating-current arc is again superior to the stroboscopic fork; for while the fork can give general indications of pulsation, it can give no indication of the angular lag referred to.

I have found these stroboscopic discs useful in another way not mentioned in the paper—in the determination of the speed of very light pieces of apparatus which have insufficient power to drive speed indicators or tachometers. For this or any work where actual speed rather than relative speed is desired the fork will be found useful, and I think that the authors of this paper should be thanked for having brought it to such a compact and convenient form.

**C. A. Perkins:** I have been doing some work with the stroboscopic fork, and any one who will try it in the laboratory will be interested to find how it smooths out characteristic curves, or any curves depending on frequency, to have an accurate device for determining the speed.

I wish to call attention to the range of speed obtained without having any shifting device. Use a tuning fork making thirty vibrations a second, or 1800 per minute, and the speeds given in the first column will be obtained. A fork which makes twenty-five vibrations instead of thirty gives the speeds in the second column, while a fork with twenty vibrations gives the speeds in the third column.

| Vibrations | 30 | 25 | 20 |
|---|---|---|---|
| full-speed | 1800 | 1500 | 1200 |
| one-half | 900 | 750 | 600 |
| one-third | 600 | 500 | 400 |
| one-fourth | 450 | 375 | 300 |
| one-sixth | 300 | 250 | 200 |

The first fork gives, without any slider, all the speeds called for in 60-cycle, alternating-current machines.

The method that I have used for observing synchronism is different from that described by Dr. Kennelly, and was suggested to me by the device which I mentioned at the Asheville meeting, for measuring the slip of motors, by means of a disc on the shaft, with a hole or slit in the disc. If such a disc, provided with a single hole, is placed on the end of the shaft of the machine whose speed is to be measured, and if the experimenter stands so that he looks through this hole at the fork, he will have one look at the fork at each revolution. Suppose the shaft to be rotating at a speed of 1800, then the two are in exact synchronism, and the fork will seem to stand still. Now if the motor speeds up five revolutions per minute, he will see the fork apparently make five vibrations per minute. Instead of adjusting the fork, the experimenter counts the apparent vibrations of the fork. They can be counted up to 150 vibrations per minute, so that the one running at 1800 vibrations can be used for all speeds between 1650 and 1950, the one running at 1500, from 1650 down to 1350, and so on. Therefore, without any slider it is possible to use three tuning forks for all speeds in ordinary testing work. At the higher speeds, one hole in the disc is sufficient, but at the lower speeds the fork is seen at such long intervals that it seems to flicker, and it will be necessary to have two or three slots, according to the speed which is to be used. I have used this fork especially for alternating-current work; it is a simple, satisfactory, and inexpensive apparatus for this purpose.

**C. H. Sharp:** I think most of us are more or less familiar with the various applications of the stroboscopic method to speed measurement, but I wish to express my sense of our indebtedness to Dr. Kennelly and Mr. Whiting for having reduced this method to such a practical and convenient form for actual use.

It is not difficult in a well-equipped laboratory to assemble a combination of tuning forks and rotating discs, or something of that kind, and make it work nicely there, but here is a thing that can be picked up and taken to any place where a test is to be performed, where we merely attach a disc to the rotating element and measure the speed accurately, or measure the slip or variation of speed accurately.

**A. E. Kennelly** (by letter): It has been found that no target is ordinarily required when the fork is used to measure the speed of alternating-current machines for 60-cycle frequency. It suffices with such machines to illumine the polar projections of the rotor, and examine these through the fork, in order to measure their speed, unless the speed and frequency should be more than 5% in error.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 29, 1908.*

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# NOTES ON THE ELECTRIC HEATING PLANT OF THE BILTMORE ESTATE

BY CHARLES E. WADDELL

Under the conditions of modern life electricity is an indispensable adjunct to the successful conduct of an establishment the size of Biltmore House; in this residence, besides the power, lighting and signal service, it is now also used for heating.

For the last two years both the hot water system and the laundry have been operated by electricity. Before entering upon a detailed description of the systems, the reasons for the substitution of electricity for fuel will be briefly stated. Under former conditions, to supply the laundry with steam and to maintain a supply of hot water, it was necessary to keep both a hot water heater and a high pressure boiler constantly fired. To operate the plant required the services of three attendants. At certain hours of every day a portion of the attendants' time was required by other duties; but in the summer months and when the house was unoccupied, their entire time was virtually bestowed upon this very small duty. Anthracite coal, costing approximately $11 per long ton, was used. The difficulty in maintaining an adequate supply, together with the noise and dirt incidental to unloading, and the cost of the removal of the ashes, rendered its use undesirable and very expensive.

The majority of southern hydroelectric corporations furnish power under certain imposed conditions as to peak, load-factor and the like, at approximately 8.5 mills per kilowatt-hour. A study of all the conditions and a review of these facts indicated that economy would result from an abandonment of fuel and the introduction of electric heat.

The plant as it stands has a capacity of 167 kw. and it has thus far fulfilled all expectations as to economy and reliability.

*Hot Water System.* The hot water system is that common to all large buildings. It consists of a loop system of piping, leading from storage tanks, and so laid out that gravity maintains a constant circulation. As a consequence, the temperature is to all practical purposes uniform throughout the house, and on no line is it necessary to withdraw a quantity of cold water before the hot comes. The stand-by losses are of course excessive, but the comfort more than compensates for the additional cost. Two storage tanks are employed, each with a capacity of 500 gal. Into the top of one of these cold water from the main enters; from the side and bottom a loop of three-inch pipe is taken out and carried to the heaters which are located some twenty-five feet lower. The heaters are the lowest point of the system.

Heat was formerly supplied by a type of heater, which closely resembled a self-contained vertical tubular boiler. To maintain an adequate supply of water at a temperature of 200° fahr. required a fuel consumption of ten pounds of anthracite coal per hour. Tests of long duration showed this to vary but little.

The electric heater is a cylindrical steel tank, three feet in diameter by five long, containing twenty flues arranged in two concentric circles, and the whole closely resembling in appearance a miniature horizontal tubular boiler. Each of the twenty flues contains a heating element of 5 kw. capacity; consequently the total capacity of the heater is 100 kw. The connecting terminals are brought out at one end of the tubes; at the other end a nut holds the elements in place. The withdrawal of the element is accomplished by simply removing the nut.

The electric heater is installed beside the coal heater and the two are provided with valves so that either or both may be used as occasion demands.

Electricity is supplied in the form of a three-phase, 60-cycle, alternating current at a potential of 230 volts. A switchboard panel is installed immediately in front of the heater and the elements are grouped thereon in three banks, each bank connected to phase, a feature of great value in balancing the load on the transformers. The power-factor of the elements is unity. This was determined by observing the current consumption first on the direct-current circuit and then on the alternating, the amperage in each case being the same.

The form of the hot water heater and the uniform rate of fuel consumption led to the conclusion that its efficiency was considerably higher than the ordinary steam boiler, and probably approximated 65 per cent. Assuming the coal to have a heat value of 14,000 B.t.u., the effective value would be 9100 B.t.u.; and since 1 kw-hr. is equivalent to 3412 B.t.u., it appeared that an input of 26.6 kw. would be an equivalent.

The approximation was so close that when the electric heater was placed in service, 30 kw., were applied; and with the exception of a few hours in the late evenings when 5 or 10 kw. more are necessary, or the early mornings when not so many are needed, this input has been varied but little.

Fig. 1—Fuel and electric hot water heaters

The energy input in any apparatus is divided into useful work and heat losses; in heating apparatus since the entire work is the production of heat, where the elements are totally immersed, the efficiency theoretically should be 100 per cent.; this is modified to some extent by the heat absorbed by the material of which the element is made.

In order to determine the actual working efficiency of the above heater, its piping was disconnected from the system, cold water was introduced, and the valve so adjusted that with a fixed input of 40 kw. the water discharged was at constant temperature. The discharge was weighed, the input meter read at the start and conclusion of the test, and from these data the net efficiency found to be approximately 85 per cent. That is to say, 85 per cent. of the input becomes available and effective, in the hot water system; the other 15 per cent. is lost in

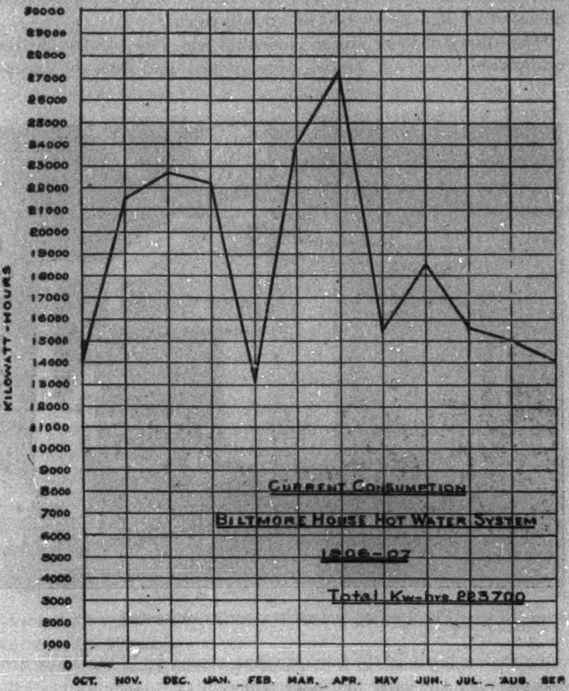

FIG. 2

radiation from the boiler shell, through the tubes, and from the attachments and piping. The author is of the opinion that the recorded efficiency is too low and may be considered as ultra conservative. Nevertheless it represents the efficiency of the plant under everday working conditions, and is not a test under artificial conditions, such as electric apparatus is often subjected to and which bear scant relation to working conditions.

The water at Biltmore contains a number of carbonates, causing boiler flues to form scale and incrustations rapidly and to an excessive degree; and with all steel piping which is subjected to a cycle of temperature change there is a continuous struggle to remove this coating. In the light of experience, although it would materially increase the cost, the use of copper flues instead of the iron ones now employed seems a justifiable expense. With a flue that would not retain scale, the formation of scale on the shell would be in the nature of additional heat insulation and would be beneficial rather than otherwise.

Ordinarily the deterioration of electric heating elements appears to be rapid; 10,000 hours is seemingly the maximum guarantee to be had. In the case of an element employed in heating water, where the element is at all times submerged, the maximum attainable temperature difference is but 180° fahr. and the deterioration is nothing like so rapid as in other classes of service.

Speaking in the dual capacity of purchaser and seller of power, the writer does not hesitate to say that electric heating for hot water service is the most satisfactory and profitable load to be had. Peak loads are the rare exception; close regulation is non-essential; and momentary interruptions to service are of no importance; and even in prolonged shut-downs the slow thermal change of the liquid is such that ample time to start the auxiliary fuel plant is afforded.

Fig. 2 is a chart showing the monthly current consumption for a year; 20,000 kw-hr. per month is considered normal. When less is recorded the consumption was purposely curtailed in order to keep the total current for the estate within the contract allowance.

The cost of the fuel heater, complete, installed, was about $350. The cost of the electric heater, complete, installed, and including switchboard, foundations, and pipe connections, was approximately $1200.

### LAUNDRY EQUIPMENT

The electric equipment installed consists of:

1 Dry room heater, capacity approximately 16 kw.
1 Mangle, 48 in. by 16 in., capacity 8 kw.
4 4-iron stoves, each with a capacity of 2 kw., total 8 kw.
1 Steam generator, capacity 35 kw.
Total capacity 67 kw.

From the main switchboard current is conducted to the laundry by three 500,000 cir. mil cables which terminate in a three-wire cabinet, the capacity of the panel being 1000 amperes. All conductors are run in galvanized conduit, the most substantial construction is followed, the aim being to secure an installation comparing favorably with steam apparatus in simplicity and durability. All laundry apparatus works interchangeably on direct or alternating current.

FIG. 3—Rear view of 100 kw. hot water heater

The dry room with a cubical contents of 640 feet is provided with three heating elements in the form of plates which are supported on porcelain insulators resting on the floor. Connections from the controlling switch box are made through asbestos covered wire and mechanical, in preference to soldered, joints are used where possible. The dryer is equipped with the ordinary form of vertical clothes racks travelling on rollers. To accelerate the process of drying an 18 in. galvanized iron flue leads from the top of the room to a nearby chimney. In laying out this apparatus it appeared feasible to supply only heat sufficient to maintain circulation; the theory being that rapid

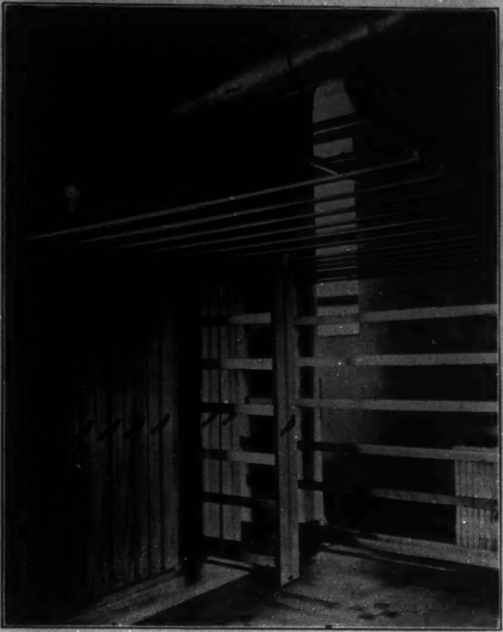

FIG. 4—Dry room, showing clothes racks and air flue

passage of warmed air would more or less mechanically exhaust the moisture.

In this connection it may be of interest to show how the equivalent heating capacity was determined. Originally the room was equipped with 108 sq. ft. of radiation in the form of 1 in. pipe. The steam pressure was kept at 60 lb. gauge; representing a temperature of 309° fahr. The temperature of the air in the dry room was usually 185° fahr., a difference of 124° fahr. Assuming that 1 in. wrought iron pipe radiates 2.9 B.t.u. per sq. ft. per degree difference of temperature; and since 1 kw-hr. is equivalent to 3412 B.t.u.; we have:

$$\frac{2.9\times 124\times 108}{3412} = 11.4 \text{ kw.}$$

Practically 12 kw.; a capacity on which all estimates were based. The discrepancy between the calculated and installed capacities is due to our use of certain elements on hand that would otherwise have been idle; and the greater capacity appears to facilitate the work.

The following is the average weekly performance, the dryer being used three days, and each day listed separately for comparison.

*Monday, March* 30, 1908. General household wash, such as shirts, underclothes, stockings, table linen, towels, sheets, etc.

| | |
|---|---|
| Number of hours used | 10.5 |
| " " articles dried | 339 |
| Weight " " dry, lb | 103 |
| Average temperature | 101° fahr. |
| Number of lb. water expelled | 84 |
| Kw-hr | 124 |

| | |
|---|---|
| lb. water expelled per kw-hr | 0.68 |
| lb. clothes dried " " " | 0.83 |
| Number of pieces " " " | 2.73 |

*Thursday, April* 2, 1908. Used for drying 18 shirts only. Shirts had been starched.

| | |
|---|---|
| Number of hours used | 4 |
| " " articles dried | 18 |
| Weight " " dry, lb | 9 |
| Average temperature | 110° fahr. |
| Number of lb. water expelled | 12 |
| Kw-hr | 68.4 |

The heater was turned on at 8 a.m. and in empty state reached working temperature in one hour. Clothes were put in 1.5 hours after current was turned on; the mere act of drying, therefore, required 33 kw-hr.

*Friday, April* 3, 1908. Second general wash.

| | |
|---|---|
| Number of hours used | 7.25 |
| " " articles dried | 276 |
| Weight " " dry, lb | 143 |
| Average temperature | 110° fahr. |

Fig. 5—Electrically heated mangle

| | |
|---|---|
| Number of lb. water expelled | 182 |
| Kw-hr | 125 |

| | |
|---|---|
| lb. water expelled per kw-hr | 1.45 |
| lb. clothes dried " " " | 1.14 |
| Number of pieces " " " | 2.20 |

Clothes ordinarily enter the dryer at a temperature of 83° fahr., having previously been raised to a high temperature in the process of boiling and washing.

The steam mangle formerly used was converted to electric service by providing the rotating drum with heating elements.

Connection with the circuit is effected by means of a 3-ring collector and carbon brushes. Three degrees of heat may be had, the maximum input is 8 kw. and the heating intensity is 475 watts per sq. ft. of surface. The performance of this machine is far more satisfactory than when used with steam; especially gratifying is the absence of leaky stuffing boxes.

The record of an average day's work is given below:

Current turned on mangle at 6.30 a.m.

Mangle started to work at 8.30 a.m., stopped at 2.30 p.m., off 45 min. for lunch; off 30 min. to cool; total hours current was on, 6.45.

Amperes, 45; volts, 118.

Two girls working. Articles mangled were: towels, table cloths, napkins, sheets, bed spreads, pillow cases.

| | |
|---|---|
| Total weight articles in lb | 221. |
| " square feet mangled | 12,256. |
| " number of pieces | 471 |
| " kw-hr | 35.8 |

All pieces were passed through twice, and many pieces three times, this accounts for the large surface area. The articles were cotton and linen.

The cost of equipping this mangle, including freight, drayage and installation, was approximately $175.

The diversity in weights, shapes and uses of the sad irons in this laundry led to the selection of electric stoves in preference to electric irons. Experience has taught that such claims were given undue consideration, and I am now of the opinion that an equipment of electric irons weighing from 7 to 12 lb. would be preferable. For heating very special shaped irons, used on laces, etc., one stove might prove necessary. A consideration entirely apart from the merits of the irons has led to their partial abandonment, and that is that with the advent of the electric apparatus the temperature of the laundry was lowered to a degree where the ironed clothes would not "air" properly, and it was found necessary to keep the coal stove going to overcome this obstacle. It appears that where clothing is at once stored, and not again immediately used, that this "airing" is essential to their preservation. With the coal stove working the use of the electric stoves was in the nature of a waste.

Below is given the record of a day's ironing using the electric stoves:

Two girls worked six hours each.
219 pieces ironed; articles were stockings, handkerchiefs, towels, napkins, pillow cases, petticoats, skirts.

| | |
|---|---|
| Gross weight, damp, lb | 63 |
| Net " dry, lb | 41 |
| Kw-hr | 24 |

It required 40 minutes to bring stoves and irons to working temperature. An iron heats in 8 minutes after being returned to the stove, and will hold sufficient heat to iron from 4 to 7 minutes, depending on the dampness of the article and the material. To properly iron a handkerchief requires 7 minutes, a bath towel 4 minutes.

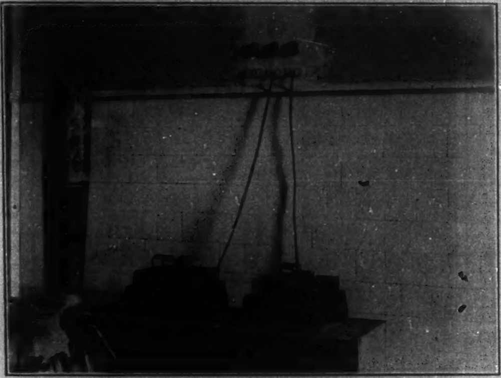

FIG. 6—Electric stoves for sad irons

The foregoing data are submitted simply as an illustration of actual performance, and represent average results; they are given in detail that others working along the same line or being confronted with new problems may glean some help from our experience. When the plant was begun we quickly realized the dearth of available data; and I believe that if all experimenters will publish the results of their investigations, facts will be gathered from the mass of testimony which will result in improved and more efficient apparatus.

Allusion has been made to the use of electric irons versus electric stoves; in connection with the former attention is called to the matter of cords and attachments. These are the weak points in this class of apparatus. The cords get damp and short-circuit, the terminals break loose, and the insulation frays off.

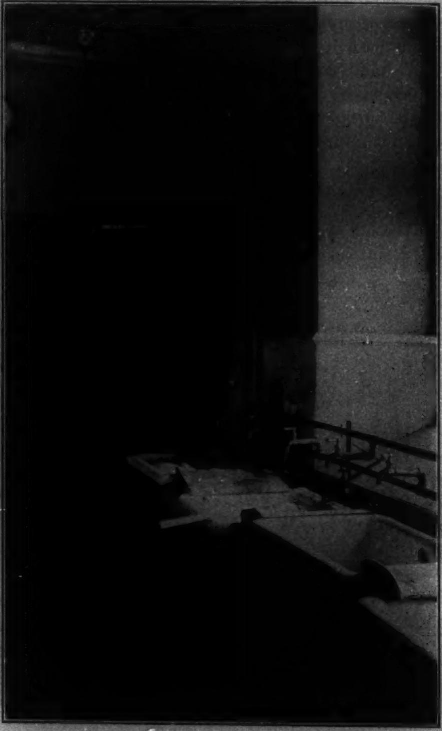

FIG. 7—Steam generator and laundry tubs

For small irons and light service the existing practice is fairly good, but in heavy work, to insure success, a more substantial equipment must be designed.

By far the most interesting piece of electrical apparatus at

Biltmore is the steam generator. With the abolition of steam service some method of boiling the clothes had to be provided. Of the several suggested and tried forms, the one in use seems best suited to the requirements. In the winter when steam heat is on the house, it is in the direction of economy to use steam from the mains. For nine months of the year heat must be secured elsewhere. Boiling the clothes is an essential process. To retain intact the steam apparatus was an obvious desideratum; to provide supplementary electric apparatus introduced complications; and a compromise was effected by generating steam with electricity, piping the generator into the steam mains, a series of valves rendering the two sources of heat interchangeable. The steam generator consists of a group of five 3-in. vertical pipes. Around the pipes the heating elements are placed. The pipes are interconnected at both top and bottom; the top is provided with a steam dome; and the whole is equipped with water column, steam gauge, pop valve and inlet water regulator. The function of the regulator is to keep the water level in the

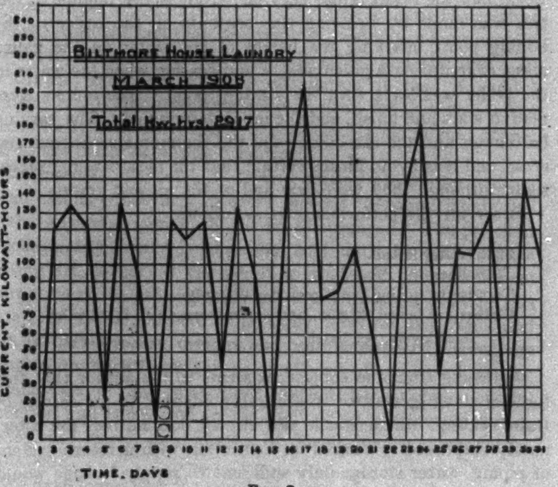

FIG. 8

boiler constant. Feed water is taken from the hot water mains. At the base, and integral with the frame, are five switches, each controlling a 7 kw. element.

Steam at practically zero pressure is conducted to five tubs and there discharged through perforated pipes located in the bottoms. The tubs are made of porcelain and contain about 2 cu. ft. each.

When new the generator was tested to determine its evaporative efficiency, this was found to be between 95 and 100 per cent. The appliances at hand were not adapted to precise work, but the result is not very far wrong in my opinion. The test was made by bringing the contents of the boiler to the boiling point, marking the height of the water on the gauge glass, evaporating a given weight and ceasing when the water in the boiler was level with the starting point. The meters were read at start and finish, and the input determined. The varying barometer and the inaccuracies of the thermometers introduced error, and it is by no means certain that the meters were exactly right, although they were new and of the highest grade.

In service the performance is as follows:

92 lb. water in tub.
7 lb. linen " "
To raise to boiling point requires 10 kw-hr.
Clothes are boiled 20 min. and current consumed is 4 kw-hr.
Total kw-hr. per batch........................14

Digressing from the subject, it seems to the author that this form of steam generator is admirably adapted to the service of train heating, where steam and electric locomotives are alternately employed. Worked in connection with a return system of piping, water storage only sufficient to supply leakage would be necessary. The generator being located on the locomotive the increase in weight on the drivers would be an advantage. The low cost, and the simplicity of the apparatus together with the fact that it would fit existing equipment should, I think, render an experiment worth while.

*Plate Warmer*—In addition to the two large classes of service that have been described, there is installed in the butler's pantry an electric plate warmer. This piece of apparatus is in the form of two shelves, each 24.5 in. by 43 in. and each with a rated consumption of 840 watts; an equivalent heating effect of 0.8 watts per square inch of surface. Each shelf is provided with its own switch, the ordinary double-pole indicating snap switch is employed for control, the wiring is of the fire-proof form of insulation, and the current supply is taken from a nearby lighting main. The lighting system being designed for operation on either the alternating bus-bars or the direct-current storage battery bus-bars, it follows that, like the laundry, the plate warmer works interchangeably on the two classes of service.

At the time of purchase this type of heating apparatus sold for approximately $6 per square foot.

*Conclusion*—As was aptly pointed out in an editorial of a representative technical paper not long since, electric heating has suffered from the fact that its economic possibilities have usually been considered from its thermal unit value; and the lesson to be drawn from the Biltmore installation is that a careful analysis of all the conditions may disclose the fact that while theoretically a disparity exists, nevertheless economy may accrue due to the better operating conditions.

Enthusiastic advocates of electric heating are to-day making broad claims which in a measure mislead the uninitiated; this in the author's opinion should be discouraged. The prices at which electric power is generally sold and the state of the heating art do not as yet admit a wholesale and unreserved usurpation of the heating field; and it is a question whether this state ever will be reached. One thing, however, is certain, and that is that Utopian dreams and unsubstantiated claims are going to do much harm and no good; and all projected heating installations of any magnitude should be accorded careful attention and considered in the light of an engineering undertaking, not merely as a matter of domestic or commercial installation.

We have found that the standard forms of enclosed fuses when continuously worked at or near their rated capacity on heating apparatus rapidly deteriorate, failing without apparent cause. For this fact I have no explanation to offer.

Experience leads to the conclusion that for heavy heating work a number of auxiliary appliances accepted as standards in lighting work will have to be either remodeled or abandoned. The temperature at which heating elements work renders the use of solder undesirable; in a number of instances that have come under our observation the terminals have melted off. The use of fire-proof or asbestos covered wire is to be preferred to rubber, even in conduit installations.

Where cords are required it would appear better construction to use flexible armored cable. For stationary apparatus the switching devices should as far as possible form an integral part of the apparatus; and where necessary to separate the two, connection between them should be made through conduit, and both switch and heating element be arranged to mechanically unite with the conduit. In the majority of places where electric heating apparatus is employed water or steam is present, and for this reason the switching devices should be accorded special attention. The open knife switch is altogether unsuitable; the enclosed knife switch some, but not much, better; and the oil switch entirely out of place. A little mechanical ingenuity bestowed upon these details would effect a decided advance in the art and would eliminate one source of trouble.

## DISCUSSION ON "NOTES ON THE ELECTRIC HEATING PLANT OF THE BILTMORE ESTATE." ATLANTIC CITY, N. J., JUNE 29, 1908

**Percy H. Thomas:** This paper is a little out of the ordinary, but the subject which it treats is well worth the attention of light and power men, as indicating how under certain conditions additional load may be obtained. I think the main lesson to be taken from what Mr. Waddell says, is that it is necessary to treat such matters as engineering problems when dealing with electric heating on a large scale, just as in the case of the boiling of water on a large scale in steam-electric plants. The heating of tea kettles and curling irons can be handled satisfactorily without special engineering training, but when large quantities of water are to be heated by electrical means of any kind it is necessary to treat the case as an engineering problem.

**Elmer A. Sperry:** Will Mr. Waddell please give us the details of his flash boiler?

**Charles E. Waddell:** The boiler is made of five 3-inch pipes, each six feet long; around each pipe a heating element is wound. The elements are externally protected and thermally insulated, with metal jacket and dead air space. All five tubes connect together at the top, forming a steam header. Water, from the hot-water system, enters at the bottom of the tubes, the quantity admitted being controlled by an automatic regulator the function of which is to maintain the water-level at a fixed point. The boiler is also provided with a low-pressure safety-valve, the discharge from which is conducted into a nearby waste pipe. In operation the device is cleanly, noiseless, and automatic.

**John H. Finney:** At what price must current be purchased in order to compare with fuel—anthracite coal, for instance?

**Charles E. Waddell:** Tests on the large steam heating boilers at Biltmore have demonstrated that under normal working conditions their efficiency is about 50 per cent. Assuming that a pound of anthracite coal has a theoretical heating value of 14,000 B.t.u., and allowing an efficiency of 50 per cent., the effective value would be 7000 B.t.u. A kilowatt-hour is practically 3500 B.t.u., hence two kilowatt-hours are equivalent to one pound of coal, assuming of course, that the kilowatt-hour is delivered at 100% efficiency.

Anthracite coal with us costs from $10 to $11 per long ton, virtually one-half cent a pound. To be on a parity, two kilowatt-hours would have to cost one-half cent, hence at a rate of one-fourth cent per kilowatt-hour.

Taken on the whole this is not altogether a fair comparison; for while it establishes the physical equivalent under working conditions between fuel and electrical energy, it does not take into account the time-element and stand-by losses, both of which are important factors in the economy of any plant.

Where the actual use of heat is a small percentage of the total time, entailing as a consequence large stand-by losses; where the service is intermittent; or where the fuel plant is small and the item of attendance large in proportion to the service, the cost of electricity could easily be two or three cents per kilowatt-hour and still effect economy.

To compete successfully with fuel in plants of magnitude—our house-heating plant for example, where the steam boiler capacity is some four hundred horse power—electrical energy at from three to five mills per kilowatt-hour would in all probability be equivalent to coal at $10 per ton.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 30, 1908.*

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# MEASUREMENTS OF LIGHTNING, ALUMINUM LIGHTNING-ARRESTERS, EARTH RESISTANCES, CEMENT RESISTANCES, AND KINDRED TESTS

BY E. E. F. CREIGHTON*

During the past year investigations have been continued in the study of lightning and the operation of lightning-arresters on transmission lines. Another effort was made to supplement laboratory studies with experimental measurements on transmission lines. Two lines were chosen well up in the Rocky Mountains of Colorado as offering the greatest facilities both from the interest of the managers and the frequency and severity of lightning storms. New types of apparatus were developed for measurements and new data were collected. The object of this paper is to describe briefly the instruments and methods used in the measurement of duration, potential, current, frequency, and the theory and practise of lightning protection and earth connections with data collected during two years of study; also resistance measurements of cement under the heating effect of dynamic current, and comments on the action of lightning-arresters.

The scope of the work is represented by the following index of subject-matter:

### CHARACTERISTICS OF LIGHTNING

*Lightning duration.*
*Duration apparatus.*

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* The writer wishes to acknowledge his indebtedness to Mr. J. A. Clay, superintendent and operating engineer of the Animas Power & Water Co., for many courtesies in the installation of the apparatus, and for subsequent auxiliary reports; to Mr. W. N. Clark for courtesies extended while observations were being taken on the high-tension lines of the Pueblo & Suburban Light & Power Co.

*Lightning potential.*
*Apparatus for measuring lightning potential.*
*Lightning current.*

### SUBDIVISION OF FREQUENCY

*Frequency of recurrence.*
*Frequency multiple stroke.*
*Natural frequency of discharge.*
*Very high frequency.*
*Quantity of lightning* $\left\{\begin{matrix}\textit{fuse apparatus}\\ \textit{ballistic apparatus.}\end{matrix}\right\}$
*Movement of charge on parallel wires.*

### MISCELLANEOUS OBSERVATIONS

*Pueblo and Suburban Light and Power Company.*
*Animas system.*
*Lightning recorder.*
*Records of discharges.*
*Lightning alarm.*
*Equipment for study.*
*Note on choke-coils.*
*Experience with a grounded phase.*
*Direct stroke of lightning.*
*Wooden versus metallic cross-arms.*

### GENERAL COMMENTS ON THE ARRESTER EQUIPMENT OF THE ANIMAS COMPANY

*Location of arresters.*
*Characteristics of the gap aluminum arrester.*
*Lightning alarm and the fuse.*
*Aluminum arresters for direct currents.*
*Temporary and permanent critical voltage of film.*

### EARTH CONNECTIONS

*Methods of tests of earth resistance.*
*Pipe earth resistance per foot of depth, Fig.* 21.
*Effect on the resistance of varying the distance between pipes.*
*Treatment to improve earths.*
*Multiple pipe earth connections.*
*Animas earth test.*
*Variation of resistance with depth.*
*Time resistance variation after salting.*
*Measurement of resistance between pipes and groups.*

*Measurements between sub-stations.*
*Measurements of resistance of tree, pole, and railroad earths.*
*Earths carrying dynamic current.*
*Form of pipe earth recommended.*
*Station grounds, resistance factor.*
*Station grounds, inductance factor.*
*Station grounds, permanence factor.*
*Lightning conductors for protecting buildings.*

### CEMENT AS A RESISTOR

*Effect on resistance of cement of various proportions of sand.*
*Change in resistance with age.*
*Behavior of cement resistors on constant potential circuits.*
*Effect of moisture on resistance.*
*Conductivity at high temperatures or pyro-conductivity.*
*Change from moisture conductivity to pyro-conductivity.*
*Concrete as a resistor.*
*Summary and conclusions on concrete resistance.*

### CHARACTERISTICS OF LIGHTNING

Before a lightning-arrester can be designed along logical lines the characteristics of the discharge which may pass through it must be known. A complete analysis of lightning phenomena on electrical transmission lines has been given by Dr. Steinmetz.* This analysis is necessary to a thorough understanding of the theory of the subject.

In considering the design of lightning-arresters, a brief classification based on the effects of lightning may be made as given below. The principle factors involved are:

1. Duration of the surge of lightning.
2. The potential values of the lightning.
3. The maximum current discharge rate.
4. The natural frequency of the lightning.
5. The quantity of electricity in the lightning stroke.

In considering the choice and operation of arresters for a transmission line, the most important of these factors is the duration of the surge. These factors will now be discussed in more detail.

1. *Duration of lightning.* Lightning from an external source (cloud lightning) is usually of very short duration. Measurements made during the summer of 1907 in Colorado, gave a

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* PROCEEDINGS A.I.E.E., March 1907.

range of 0.04 sec. to 0.0001 sec. Cloud lightning has been known to continue for longer than one-half a second in rare cases. Lightning from an internal source (accidentally grounded phase, switching, etc.) often continues over a period of several minutes, or even several hours.

Lightning frequently recurs in successive strokes. A number of measurements were made on an idle line which gave as high as seven separate discharges in one second. In the lightning-arrester these multiple strokes give the effect of long duration.

FIG. 1

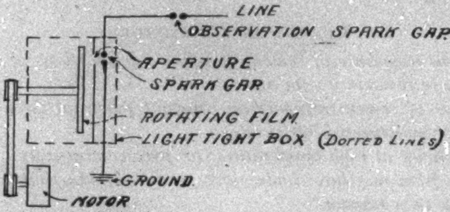
LINE
OBSERVATION SPARK GAP
APERTURE
SPARK GAP
ROTATING FILM
LIGHT TIGHT BOX (DOTTED LINES)
GROUND
MOTOR

FIG. 1.—Revolving film duration apparatus

*The duration apparatus.* Two different pieces of apparatus were used to measure the duration of lightning. They are shown diagrammatically in Figs. 1 and 2. For very short duration the apparatus shown in Fig. 1 was used. This apparatus consisted of a spark-gap in front of a rapidly revolving photographic film. Figs. 3, 4, and 5 are records from this machine; they show several different discharges which are made to fall on an unexposed portion of the film by moving in the aperture

FIG. 2

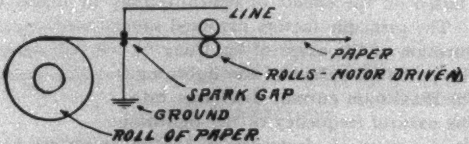
LINE
PAPER
ROLLS - MOTOR DRIVEN
SPARK GAP
GROUND
ROLL OF PAPER

FIG. 2.—Moving tape duration apparatus

to a lesser radius on the film. Knowing the speed of rotation of the film, the duration of the discharge was measured. Calculations were made on 36 discharges. Nearly all of the storms that caused the discharges were distant from the station. This may partly account for so many short durations. There were two strokes expressed in hundredths of a second, seventeen in thousands of a second, and sixteen in ten-thousandths of a second. Besides the duration and multiple strokes, these exposures show frequencies of the order of the line frequency. Each exposure is divided into a broken line which represents the frequency of alternation of the discharge. This frequency, about 3000 cycles per second, was further analyzed into a higher

FIG. 3.—Record from revolving film duration apparatus. This shows one multiple discharge consisting of eight single discharges marked (a) and one single discharge marked (b)

frequency by the lightning frequency meter to be described later. Three thousand cycles is beyond the frequency that can be measured by an oscillograph. Where several segments of a circle of the same radius are shown (Fig. 4), multiple lightning strokes occurred; these strokes occurred in such rapid succession that they appeared as one to the eyes focused on the observation spark-gap.

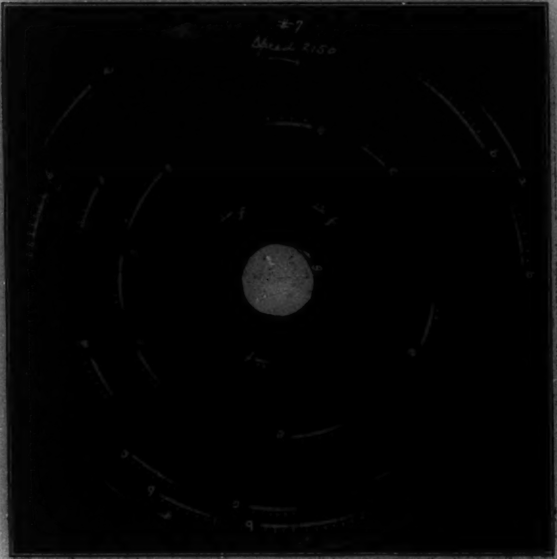

FIG. 4.—Record from revolving film duration apparatus showing six multiple strokes marked *a*, *b*, *c*, *d*, *e*, and *f*. The small dots at the side of most of the exposures are ink marks to emphasize the markings of the natural frequency of the discharge for fear they might not show up in the usual process of reproduction. This record is unusual in the number of multiple strokes

Fig. 5 is the only record of a discharge that did not show a natural frequency of oscillation. This may have been due to earth resistance being exceedingly high under the line where the lightning charge was set free. A fuller explanation is attempted later.

For the measurement of longer durations of lightning, the paper tape apparatus shown in Fig. 2 was used. The tape was drawn through a spark-gap between line and ground at a uniform rate. This apparatus attached to an idle line showed multiple strokes; in several instances, as many as four strokes were distributed over one second. In these multiple strokes the successive discharges could be detected by the ear. It usually produced a rattling sound. Without the apparatus the noise might have been attributed to echoes. Records of multiple strokes and duration as given by the tape will be shown later in this paper.

Fig. 5.—Record from the revolving film duration apparatus showing two single discharges. Discharge (a) is the longest one recorded. If there are any natural oscillations the speed of the film is too low to show them

2. *Lightning potential.* In cases of direct strokes from the clouds to a transmission line, the potential at the nearest insulator builds up so rapidly that even the small inductance of the straight line wire presents a relatively high impedance to the flow of the electrical charge along the wires, away from the point, and consequently it spills over the insulators and down the poles to the ground. In this extreme case a lightning-arrester situated some distance away will give no protection to the point struck. If the electrical charge can be prevented from jumping around the insulator by high dielectric strength or overhead ground-wire the charge travels to the nearest lightning-arrester. During this movement it loses greatly in potential and somewhat in natural frequency. In every case of induced static charge from the clouds, lightning potential on the line is always greatest directly under the cloud that is discharging. A number of cases

**Fig. 6.**—An accidental discharge which passed through the right forearm from the wrist to the elbow and out through an arc to an iron support. This produced complete paralysis of the forearm which lasted several hours. The injury was painless except for the after-effects of the surface burns

were observed last summer in Colorado when a storm was over an unprotected station about three miles from the main sub-station in which the lightning jumped three and one-half inches over switch bushings at the unprotected station instead of being discharged by a gap set at 0.4 in. (one-eighth as large) at the main sub-station.

If the lightning potential is due to an internal surge of electrical energy between static and electromagnetic energy, then the high potential will exist across the junction point of the parts of the circuit acting as condenser and reactance-coil respectively. This may for example, be, one coil or all the coils of a generator or transformer.

*Apparatus for measuring potentials.* Practically the only apparatus which indicates the potential of lightning of brief duration is the well known needle-gap. A needle-gap without series resistance would short-circuit the dynamic potential and therefore could not be used. The use of a reasonable resistance in series with a single needle-gap affects its spark potential but slightly even for high frequencies. The electricity travels along the resistance and throws the static stress on the needle-gap and produces a spark. The volume of spark which takes place decreases as the resistance increases. Since it is necessary to record this spark the resistance must be kept at least low enough to permit this. As an example of the effect of resistance on the relative spark potential at high frequency the following is given: two needle-gaps placed in parallel, the first set at 1 in. having no resistance, and the second having two 8 in. rods with carborundum as a base, known as 50,000-ohm rods (actually less at high potentials). The second gap would not spark when set on 1 in. but would, without fail, spark simultaneously when set at 0.9 in. The potential, obtained from a leyden jar and static machine, had an initial value of about 60,000 volts, was very suddenly applied, and had a frequency of about two million cycles per second. At 60 cycles the spark potential of the needle-gap was not affected by this series resistance. This condition of high frequency is probably more severe than will be met on a transmission line.

One needle-gap never actually measures lightning potential unless the applied potential should happen to be equal to the spark potential. If a needle-gap sparks it shows the pressure reached its spark potential but it may have gone very much higher. By using several gaps in parallel the potential may be measured with a rough accuracy depending upon the number of gaps in parallel and the differences in their setting. Fig. 7 shows diagrammatically part of such a lightning potential meter.

In each circuit is a fuse, a needle-gap, and a resistance limiting the dynamic current to about one-half ampere. In operation the impressed potential must be between the largest gap that sparked and the next one above. Since the gap must be set after each lightning stroke, the form of the meter is modified to give a measurement of several successive strokes, to record the time, and to give automatic resetting. Fig. 8 shows one leg of this automatic resetting device.

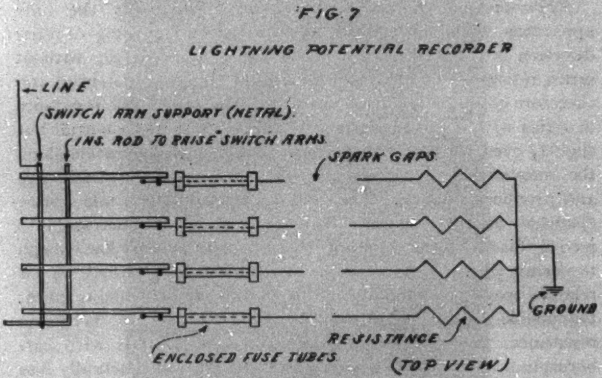
FIG 7
LIGHTNING POTENTIAL RECORDER
LINE
SWITCH ARM SUPPORT (METAL).
INS. ROD TO RAISE SWITCH ARMS
SPARK GAPS
GROUND
RESISTANCE
ENCLOSED FUSE TUBES
(TOP VIEW)

Fig. 7.—Plan of lightning potential recorder

In this leg the gaps are all equal. From the switch arm a thread is run to a pen which draws a line on a paper tape moved by clockwork. This records the exact time when each gap sparks. Since a lightning recording device can be placed on each arrester, the combined results of the two will show the relative efficiency of the arresters for each discharge. For example, the needle-gap of the potential recorder may be set on 2, 2.5, 3, and 4 times normal line potential. To get the proper operation of the potential recorder care must be taken in its design to avoid producing the effect of a grounded phase by the arcing of one phase only.

3. *Lightning current.* The maximum value that the lightning

current may take has an important bearing on the design of the arresters. Until recently it was found necessary and expedient to install some resistance in the arrester circuit to limit the dynamic current which usually follows the lightning discharge. This resistance limits also the lightning discharge current, and by its ohmic drop (*I R*) prevents the lightning potential from decreasing rapidly.

If the lightning discharge current is limited by ohmic resistance it is easy to calculate what current can discharge at double line voltage. Double voltage is usually within the limiting safe value. Such a comparison of arresters gives their relative values of protection against lightning.*

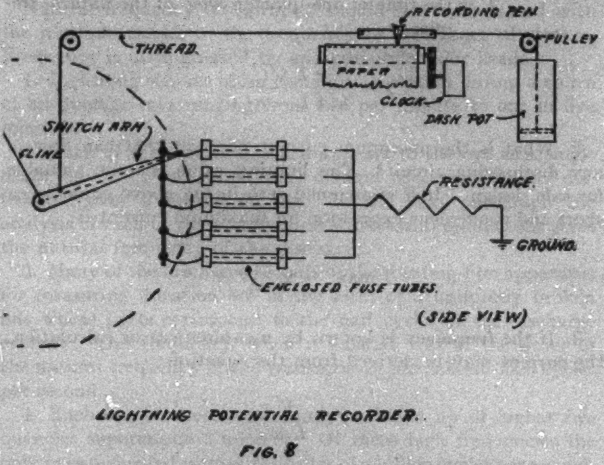
RECORDING PEN
PULLEY
THREAD.
PAPER
CLOCK
DASH POT
SWITCH ARM
LINE
RESISTANCE.
GROUND.
ENCLOSED FUSE TUBES.
(SIDE VIEW)
LIGHTNING POTENTIAL RECORDER.
FIG. 8

FIG. 8.—Elevation of lightning potential recorder

The actual measurement of the lightning current is usually more difficult than the measurement of the high frequencies. Several conditions will be outlined here. Since concentrated capacity and inductance are used in the laboratory, these equations are convenient to use here.

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* The time constant or natural frequency enters as a factor. A large time constant of the lightning allows of higher resistance in the arrester circuit.

1. In any circuit containing a low resistance, what is the current per volt of impressed electromotive force?

$$I = \frac{2\sqrt{C}}{\sqrt{(4\,L - R^2\,C)}} \quad \frac{1}{\varepsilon^{\frac{R\,T}{2\,L}}}$$

In which $C$ is the capacity in farads,
$L$ is the inductance in henrys,
$R$ is the total ohmic resistance,
$t$ is the time of one-quarter cycle of the natural frequency.

$$t = \frac{\pi\,L\,\sqrt{C}}{\sqrt{4\,L - K^2\,C}}$$

2. What is the maximum current per volt that can flow in any discharging circuit? The limiting value is more valuable for safe design. If $R$ is assumed zero in the above equation, a short and convenient expression for maximum current is:

$$I\ \text{max.} = \sqrt{\frac{C}{L}}\ V$$

3. If the frequency is known by measurement or calculation, the current may be derived from the equation

$$I = \frac{V}{L\,\omega}$$

4. The maximum current may be estimated from calculation utilizing the frequency, quantity of electricity, and logarithmic decrement. As an example of calculation of a testing circuit in the laboratory the following is given:

Three one-gallon leyden jars are connected in parallel, and this set is connected in cascade or series with an equal unit by means of about seven feet of No. 0 wire.

Capacity of each jar is about $144\text{x}10^{-11}$ farads

Capacity of all the jars is about $216\text{x}10^{-11}$ farads.

Inductance is about $24\text{x}10^{-7}$ henrys.

$I$ maximum = 0.03 ampere per volt. At 100 kilovolts, the possible maximum current is 3000 amperes.

The frequency is $n = \frac{I}{T} = \frac{1}{2\pi\sqrt{L\,C}} = 2.25$ millions.

In regard to accuracy of the calculated value of frequency, an error in either capacity or inductance is reduced by the square root in the result. An error of 25 per cent. in these values gives an error of only 5 per cent. in the frequency.

The resistance which will just destroy the oscillatory discharge of the leyden jar circuit in the foregoing description is 7000 ohms.

### SUBDIVISION OF FREQUENCY

Natural frequency of lightning should not be confused with the multiple stroke or the frequency of recurrence of strokes. Frequency is distinguished by analysis under four heads.

1. Lightning strokes often come into a station during a storm at an average rate ranging from two per minute to one in five minutes.

2. Each of these flashes, which appears to the eye as a single flash, may often be two or more distinct successive strokes distributed over a second or less. In the next paragraph the analysis of each of these individual strokes into oscillations gives the natural frequency of the discharge.

3. Many of the discharge records of the rotating-film apparatus for measuring duration are in the form of a uniformly broken line whose parts correspond to the half cycles of the discharge current. This frequency, when it existed, was of the order of the natural frequency of the transmission line, about 3000 cycles per second.

4. Each one of these waves may be made up of higher frequencies superimposed upon it. Of these high frequencies the only ones measured were of the order of a millon cycles per second.

*Comments and data on the four subdivisions.* 1. Frequency of recurrence, or rapidity of lightning discharges. A note of all the discharges during two storms which came into the substation from three circuits and were recorded on the tape lightning recorder is herewith given.

Condensed record of second storm of August 12, 1907. First discharge 1:10:36; last discharge 1:59:4, p.m. Total number of discharges 42. Average number of discharges about one per minute. Maximum number of discharges per minute was three. In the second storm of August 9, 1907, there were 33 strokes in 43 minutes. The rapidity of discharge in these storms was not unusual.

2. *Multiple strokes.* In the second storm of August 12, there were two cases of multiple strokes. In each case there were two strokes within a second recorded on the paper tape. In the second storm of August 9, 1907, there were five cases of multiple strokes. When multiple strokes followed each other more rapidly than 0.2 second, the paper tape would not show a separation. The more rapid multiple strokes are recorded on the duration apparatus, Figs. 3 and 4. Discharge marked *a*, Fig. 4, shows three distinct strokes; discharge marked *b*, shows five; discharge *c*, shows two; discharge *e*, shows seven; discharge *f*, shows three; and discharge *g*, shows one. In this storm multiple strokes seem to have been the rule. Except for the records shown in Figs. 3 and 4, the films show mostly single strokes.

3. *Natural frequency.* In Fig. 4 the broken line of the discharge is made more evident by drawing definite ink lines at the side of the record for each half cycle where the record was sufficiently distinct to be definite. This is done lest the markings be lost in the reproducing processes. The accuracy of measurement is not high, so the frequencies recorded are divided into eight groups as follows: one stroke of no oscillation, Fig. 5; one stroke at 840 cycles per second; eight strokes at about 1400; six strokes at about 2000; two strokes at about 2500; twenty strokes at about 3000; and one stroke at 4000 cycles per second.

A careful inspection of the records brings out irregularities in the time between half cycles of some of the records, especially at the beginning of the discharge. This might be expected from the theory, but the constancy and regularity of the discharge of the line to earth at about 3000 cycles is surprising. A tentative explanation of the phenomena is herewith given: out some distance on the line a storm cloud hovered and induced a charge on the line which leaked over the insulators. The induced charge may have covered a mile or more of the line and may have been located at any point between the middle and end. The cloud discharged and freed the induced charge. The charge immediately tried to spread over the entire line. Apparently there was considerable dissipation of energy in the earth resistance. The first effect, usually, is a static wave of potential which reaches the end of the line where the instrument is placed, jumps the two series gaps of the instrument to the earth, pours out the entire charge to earth, overshoots the zero potential, and leaves the line oppositely charged. The gap sparks again and the potential again overshoots the zero and again the charge of the original sign covers the line. During each oscillation the current passes through the resistance of the earth, line, and spark, which uses up the energy. Finally, after a few half cycles, the potential can no longer jump the gaps to ground and the remaining charge finally settles down evenly distributed over the whole line.

Theoretically, the location of the freed charge on the line relative to the ends should make a difference in the rate of discharge to ground. Since one end of the line is insulated, the part of the charge which travels to this end should be reflected back to the discharging end after that end has begun to discharge. This should change the regularity of the discharge, more or less, according to the location and length of line covered by the original charge. In confirmation of this

FIG 9.—High frequency recorder as installed in the high-tension gallery of the sub-station

theory several records show an irregular spacing and minor peaks of current at the beginning; after a few half cycles, however, the effect of these reflected waves disappears and the line seems to oscillate as a whole. It may be noted here that the number of half waves in the record furnishes a means of estimating the minimum potential that the initial charge might have had.

4. *Very high frequencies.* In Figs. 3 and 4 the discharge was analyzed into waves having a frequency of the order of the period of the line. The next step is to analyze the harmonics in each of the waves. There may be two explanations of the presence of the higher frequency: either the cloud lightning may discharge with a frequency of the order of one million cycles per second, or the traveling wave along the line may meet with inequalities of capacity and induction which cause ripples in the waves. To detect these waves a recording high frequency meter was constructed. The meter as installed in the high-tension gallery of the Silverton sub-station is shown in Fig. 9. It consists of nine vertical coils of wire each closely wound in a single layer on a glass tube. The glass tubes and the wire are of varying sizes so as to give each one a different value of natural frequency.

The fundamental frequency and frequencies of the higher harmonics of each coil are given in the following table.

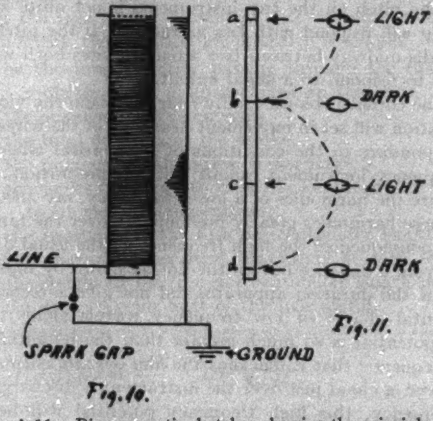
| Coil No. | Fundamental frequency | Third | Fifth | Seventh |
|---|---|---|---|---|
| 1 | 120,000 | 360,000 | 600,000 | 840,000 |
| 2 | 175,000 | 525,000 | 875,000 | 1,225,000 |
| 3 | 232,000 | 696,000 | 1,160,000 | 1,624,000 |
| 4 | 290,000 | 870,000 | 1,450,000 | 2,030,000 |
| 5 | 364,000 | 1,092,000 | 1,820,000 | 2,548,000 |
| 6 | 593,000 | 1,779,000 | 2,965,000 | 4,151,000 |
| 7 | 721,000 | 2,163,000 | 3,605,000 | |
| 8 | 890,000 | 2,670,000 | | |
| 9 | 1,130,000 | 3,390,000 | | |

Some of these values overlap and give a check on the results; for example, the third harmonic of tube No. 5 almost coincides with the fifth harmonic of tube No. 3.

The high-frequency instrument utilizes the principle of the stationary wave. One coil of the meter is represented diagrammatically in Fig. 10.

Parallel to the tube is an antenna toward which the brush discharge takes place. The tube is represented as receiving an oscillation which is three times its natural frequency of vibration. This is indicated by the two patches of brush discharge.

Fig. 11 shows the distribution of potential along the tube. An electrical wave passes up the tube to the dead end *a*, is reflected back, and meets the adjacent incoming wave moving in the opposite direction. When the waves cross each other at *b*, they have opposite potentials and neutralize each other. When the first reflected wave arrives at *c*, it crosses the peak of the next wave when both waves have the same sign of potential. The result is double the potential of one wave. Since, if the tube is in tune, all incoming and reflected waves cross each other at the same point, stationary waves are produced on the tube. The presence of these stationary waves can be shown by holding a small vacuum tube near the coil, Fig. 11. This much has been used by wireless telegraph engineers in conjunction with a capacity which can be varied to resonate the tube to the oft-repeated waves from a wireless sender. No such adjustment can be made in studying lightning, as the discharge comes in without warning, is usually over in one thousandth of a



FIGS. 10 and 11.—Diagrammatic sketches showing the principle of operation of a high-frequency recording unit second, and does not repeat itself. An automatic recording device was found in employing a long photographic film in the static field between the tube and antenna, Fig. 10. The location of the film had much to do with the success of the results.

The conditions of the operation of the instrument may be explained by their analogy to musical resonance.

*a.* If a piano is pedaled to free the strings from their individual dampers, and a note is sounded on a cornet at some distance, the string on the piano corresponding to the tone of the cornet will be set in vibration and can be heard after the cornet note is stopped.

*b.* If the pitch on the two instruments is not quite identical, the string will respond with less vibration. If the pitch of the cornet falls midway between two adjacent wires both wires can be made to respond to a slight extent.

*c.* If the cornet is blown loudly near the piano the violence of the vibration will set in movement nearly all of the wires.

Corresponding to the conditions of the musical analogy, the high frequency instrument cannot, without precaution, be used to measure the harmonics of a lower frequency, say 3000 cycles, unless these harmonics greatly predominate over the fundamental. In consequence, the high frequency of the usual discharge coming from a distance out on the line as shown by most of the records of the duration apparatus did not give a record. The fundamental charge of low frequency travels along the coil, and its potential is so much greater than the potential of the higher frequency that it blackens the film over its entire length. If, however, a cloud just over the instrument is discharging at a high frequency, this high frequency potential will be forced onto the line and may affect the instrument.

If the difference of potential of the fundamental wave is limited to a small value by using a spark gap, the harmonics become relatively more effective. Due to the unpropitious conditions on the line, adjustments, and lack of facilities, only two of the records were of value.*

The high frequency recorder is better adapted to the study of cloud lightning directly. The receiving antenna can be made with a large coefficient of damping so that sensibly nothing but the forced oscillations will affect the film, and furthermore, local sparks can be eliminated.

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* The entire credit for the measurements obtained are due Mr. Peek for his painstaking and tireless efforts.

*Quantity of electricity.* Fuses have been used to indicate the relative severity of a lightning stroke, but a fuse in itself gives no absolute information regarding the quantity of electricity in a lightning stroke. The factor of duration enters, and this depends on the damping effects of resistance various losses during the discharge, and the initial lightning potential. A small quantity of electricity oscillating for a long time may blow a fuse, while a hundred times as much discharging through a damped circuit might leave it intact.

The essential features of the apparatus for measuring quantity are a fuse that just blows and a duration apparatus that records the number of oscillations through the fuse. If the refinement of taking the logarithmic decrement into account is neglected for the moment, the equation for quantity is simple.

Let $Q$ be the total quantity passing through the fuse (some multiple of the quantity freed on the line),
$I$ the average effective current,
$t$ the total duration of the stroke,
$n$ the number of half-cycles of discharge,
$J$ the joules of energy to raise one centimeter of the fuse to its melting temperature,
$R$ the resistance of the fuse per centimeter length,
$T\phi$ the rise of temperature, centigrade, to melt the fuse,
$w$ the weight of the fuse per centimeter length in grams,
$S$ the mean specific heat of the fuse metal.

Then

$$J = I^2 R t = \frac{Q^2 R}{t}, \quad Q = \sqrt{\frac{J t}{R}}$$

In which $J = T \times w \times S \times 2.4$, and lightning $(q) = \frac{Q}{n}$

Nothing but approximations are necessary in these calculations, therefore the heat radiated from the fuse during the brief period of the discharge is neglected or rather allowed for by choosing, for calculation, the size of fuse one above the fuse melted out. The larger the fuse that is blown the less the relative value of radiation, because the surface relative to the volume is also less. Our interest in the quantity of electricity in the lightning stroke increases as the quantity becomes greater, and fortunately, for the upper value, the accuracy correspondingly increases. Other things being constant, it requires a fuse of four times the weight to hold a charge of twice the quantity.

There may be a fraction of the original quantity left on the line after the discharge has passed due either to a gap in the circuit or to the gap of the fuse that blows. This residual quantity has nothing to do directly with the result because there has been already more than one oscillation. Its indirect bearing is beneficial if approximate calculations are being made. The fewer the oscillations recorded the nearer is the average quantity to the original maximum quantity set free on the line.

The arrangement of the apparatus for measuring the quantity of electricity is shown in Fig. 12. A duration recorder is shown in series with three magazines of fuses. Each magazine of fuses consists of a set of parallel fuse wires placed one above the other. At one end they are connected to a vertical post of some insulating material and at the other to a metallic post. In front of this fence of fuse wires is a vertical post carrying a hinged arm which rests on the top wire. As each fuse blows the arm drops automatically on the next fuse below. All the fuses in one magazine are the same size but the fuses are graded in size in the separate magazines. In operation the arc will hold in the vapor of the small fuse while a larger one melts. For this reason a metal of good arcing quality, like lead for example, is preferable.

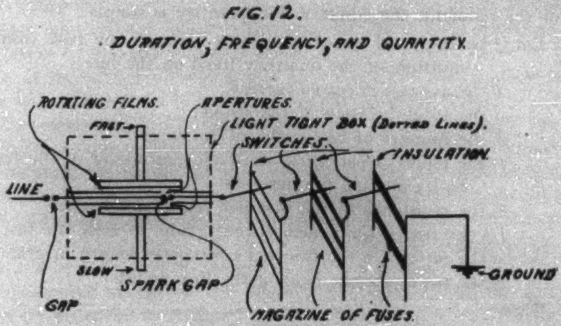

FIG. 12.—Combined apparatus for measuring duration, frequency, and quantity of electricity

Another method of making the calculations for quantity of electricity is by calibration of the fuses using an oscillograph to measure current and time. Using a voltage too low to maintain an arc, currents of increasing values with the same size fuse are used and a curve made between the factors of current and time. For very short intervals of time the equation seems to show independence of the radiation and is:

$$I^2 R t = \text{constant}, \qquad \text{or } I^2 t = k$$

Using the data taken from one of the tests, which was a heavier stroke than the average but not so severe as some others, a value of 0.032 coulombs was found for the total quantity that passed. It happened that multiple strokes occurred each time a fuse test was made, so a near approximation of the quantity of lightning induced by the cloud cannot be made on account of the radiation during the interval of the multiple strokes. A rough approximation of the quantity in this case is 0.003 coulombs. If this quantity of electricity was spread over a mile of line having a capacity between line and ground of 0.01 microfarads, the initially impressed voltage would be about 600,000 volts. The question whether a voltage of this nature will jump an insulator or not, is not solved by impressing a constant voltage of the same value on the insulator to determine if it will spark over, but it is entirely a matter of the relation of the dielectric-spark-lag of the insulator to the time constant of the line wire. The inductance of the line opposes momentarily the spreading of the charge over the entire line. A wooden cross-arm gives a much greater dielectric-spark-lag than an iron cross-arm. This subject is treated experimentally later under its appropriate head.

A refinement in the calculation of quantity requires the integration of the instantaneous value of current over the duration of the discharge.

$$Q = \int i \, d t$$

in which $i$ may have the approximate form

$$i = k_1 \varepsilon^{-\frac{Rt}{2L}} \sin k_2 t.$$

*Quantity meter of ballistic principle.* Instead of using fuses, which are destroyed and have to be replaced, an ordinary hot-wire ammeter may be used if it is properly calibrated and the hot wire sufficiently insulated so that the drop of potential due both to $I R$ and $L \omega$ do not cause a short circuit. In the laboratory this method is convenient but in the study of cloud lightning effects the hot-wire ammeter has the disadvantage of leaving no record and therefore requires constant watching and patient waiting.

If quantity and frequency are known, this method can be used to measure duration or number of cycles.

*Movement of charges on parallel wires.* It is seen from the low frequency of the discharges of Figs. 3 and 4 that the concentrated charge under a cloud flattens out over the line when set free. The free movement of the wave seems to be greatly retarded by the surface resistance of the earth directly under the line wire. Incidentally it may be noted that a short line will be harder hit than a long one by the same cloud conditions, although, by the law of chance, not so often.

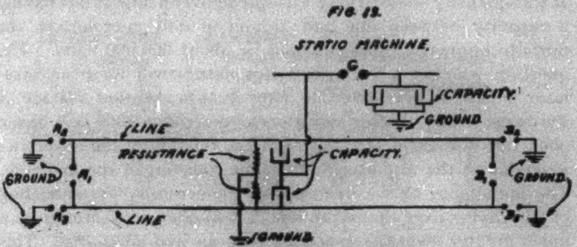

FIG. 13.—Laboratory test illustrating the mutual induction between two moving lightning charges

There is another phenomenon observed which modifies somewhat the potential of the traveling wave. This was first observed on a two wire circuit. When equal induced lightning charges on the two parallel wires are freed, electro-magnetic induction will oppose the flow in the same direction. With a fixed length of gap at each end in each wire of a two wire circuit, only one gap would spark unless the discharge was either unusually heavy or quite near the station. This same phenomenon was checked up in the laboratory on a circuit represented in Fig. 13.

The first test utilized the gaps $A_1$ and $B_1$ only. When properly adjusted, both of these gaps sparked simultaneously. The second test utilized the gaps $A_2$, $A_3$, $B_2$ and $B_3$. Under certain conditions of test the wires would spark to earth invariably at opposite ends. These tests seem conclusive of the tendency of the mutual inductance to force the equal charges in the opposite direction along the circuit. Line to line discharges due to cloud lightning sometimes take place. The above phenomenon no doubt is partially the cause of such discharges.

A brief description of the two lines on which observations were made follows.

*The Pueblo and Suburban Light and Power Co.* The Pueblo and Suburban Light and Power Co. has 24,000-volt lines between Pueblo and Victor (altitude 10,000 ft.), Colorado. The power house is at Skaguay, somewhat lower than the Victor sub-station. General observations only were made here. The measuring instruments did not arrive until the beginning of August and work was then taken up on the Animas Power and Water Co's. lines as the storms were more frequent in that locality in the late summer. All the new measurements were made on the line during the latter part of August, 1907.

*The Animas Power & Water Co.* The Animas Power & Water Co. transmits energy from the power house (8,000 ft. altitude) to the sub-station (9,500 ft.) at 43,500 volts, with the neutral grounded at the power house. There are two separate lines, one at the bottom of the cañon to minimize the electrical disturbances in summer, and the other carried directly up 1000 ft. to an elevated plateau to minimize the trouble due to snow slides in the winter.

At the main substation, the voltage step downs to 17,000 volts delta. On the 17,000-volt system there is one customer's station (100 kw. capacity) with grounded neutral; but this seems to have no beneficial effect when recurring surges play over the system.

On the system are about 30 customer's stations, all mines or mills except the city circuit of Silverton. The lines run along the cañons, up the gulches to the mines, and over the ridges. In two places the lines reach an altitude of over 13,200 ft. The difference in altitude is about 4000 ft. on the 17,000-volt system, and 5200 ft. on the entire system. The system covers a lightning area estimated at 270 square miles. The 17,000-volt circuit is not in duplicate. The feeders have sectionalizing switches at several points. At the mines, the potential is transformed to 440 volts and, in several places, is carried overhead for several hundred yards to different tunnels.

The severity and frequency of lightning storms during the season has been previously noted. Two storms often occur in one day. Storms sometimes hover over some part of the system for 24 hours. In that neighborhood it seems that the cool winds from the north meet the warm winds from the stretches of desert to the south. It is probable that the problem of lightning protection here is as difficult as any place in the world.

Some of the methods and instruments for measuring lightning potential, frequency, duration and quantity have already been described. A most valuable aid was a lightning recorder—a development of the tell-tale paper.

*Lightning recorder.* One of the types of lightning recorder used consisted of a cylinder, uniformly rotated by geared power, carrying a ribbon of paper, Fig. 14. Four electrodes pointing toward the axis of this cylinder and separated from the circumference by clearance only, were connected to the lightning-arrester. This recorder was placed at the neutral or multiplex connection of the arrester having one electrode connected to each phase and one to the ground. This arrangement differentiates between line to line, and line to ground discharges. A single-phase induction motor was used for power in the first set of instruments. This power was carried through multiple gears which permitted of four speeds in multiples of tens. Most of the records were taken with a speed of about 0.1 in. per second. Later designs of recorders using clock work have the advantage of greater uniformity of speed and independence of the voltage and frequency of the circuit.

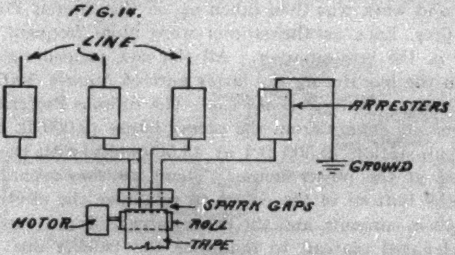

Fig. 14.—Lightning recorder to show the discharges through a lightning-arrester

The records show the exact time and phase of the discharge, and, by the size of the punctured hole, give an indication of the relative quantity of electricity discharged. If, however, the arrester is connected to a circuit supplied with power, the dynamic current will burn away all trace of the original hole produced by the static discharge. When a phase is accidentally grounded, the record tape shows which phase is producing the surges and how long the trouble lasts.

*Lightning discharge records.* Some typical and unusual records of lightning discharges from lines are herewith reproduced. Fig. 16 is the record of an aluminum arrester taking a recurrent surge due to an arcing ground to the third phase. After 2 seconds of heavy discharge the trouble nearly cleared itself but it was 25 seconds before the surges were entirely over.

FIG. 15.—Three discharges of lightning through a cone-type aluminum arrester on an idle line. The central hole is the largest recorded, due entirely to static, during the season. The discharge caused a loud report

Fig. 17 shows three simultaneous records; to the left is a record of 4 multiple strokes on the telephone circuit, in the middle the discharge of an aluminum arrester, and to the right the discharge of a liquid-electrode arrester. The telephone record shows tiny holes encircled by ink rings. This is a static hole of usual size on the telephone circuit when the storm is over five miles distant. The aluminum arrester record shows a somewhat larger hole which was enlarged by the dynamic current. The liquid-electrode arrester record shows large holes burned by the dynamic current and shows furthermore that the four discharges were so close together that the holes burned into one. Phase three, with the same single gap setting, did not spark. The aluminum arrester was inside the choke-coils and only one of the four discharges passed through the choke-coil. It should be

FIG. 16.—Discharge of continuous lightning through an aluminum arrester. There was an arcing ground in phase 3. Phase 3, shows an initial discharge only. Phases 2 and 1 discharged heavily to ground during 3 seconds, then the ground began to clear itself. The total time of discharge was 40 sec. The records of longer discharges cannot conveniently be reproduced here

FIG. 17.—Three simultaneous records. To the left, the telephone arrester shows multiple strokes; in the middle, the aluminum arrester shows a single discharge; and to the right, the record of the multiple discharges of phases 1 and 2 to ground through the liquid-electrode arrester.

FIG. 18.—Two simultaneous records of discharges through liquid-electrode arresters

noted that these four distinct discharges gave the effect on the arrester of a continuous discharge about one second long.

Fig. 18 shows two discharges of the liquid-electrode arrester. These discharges were normal. These arresters were on different feeders and discharged simultaneously.

Fig. 15. This record is most unusual and remarkable. This tell-tale paper was in the gap between a cone-aluminum arrester and ground on a 24,000-volt line without dynamic potential. The static discharge usually makes a very small hole. The static discharge which punctured the middle hole made a loud report. This was the heaviest discharge recorded during the season. It produced no effect on the aluminum arrester.

*Lightning alarms.* Since the aluminum arrester is designed to operate continuously for a half hour or more, an alarm may be attached to all these arresters, so that an operator in his office may know when the arrester discharges. He can begin to take precautions to clear the line if the trouble is continuous.

As a convenience in the Colorado tests, Mr. Peek arranged a lightning alarm on the principle of a wireless telegraph receiver which would ring a bell for cloud lightning, or grounded phase, when such occurred on any part of the system.

*Equipment for study in the main sub-station of the Animas Co.*

1 High frequency recorder on 43,500-volt dead line.

1 Duration meter and low frequency meter on 43,500-volt dead line.

3 Lightning discharge recorders on three telephone circuits.

2 Lightning discharge recorders on 17,000-volt liquid electrode arresters, outside of choke-coil.

1 Lightning discharge recorder on 17,000-volt aluminum cell arrester, on bus-bars.

1 Lightning potential recorder on 17,000-volt line.

1 Lightning alarm (general).

1 Quantity recorder on three telephone circuits.

1 Quantity recorder on 43,500-volt dead line.

To show if discharges were not taken by lightning-arresters, the following device was used:

In the customer's stations, all points of the line which had less insulation than the main line—for example, leads from oil switches and transformer bushings—were wrapped with white paper tape or covered with sheets of paper. Only a few of the customer's stations had lightning-arresters installed. It was vital to locate the trouble. There was no indication in the main station, except the action of the circuit breakers from the resulting short-circuits. Subsequently, the short-circuits could be located by means of the arc marks on the tell-tale papers. Cloud lightning caused several short circuits during the season but in no case did such trouble, due to cloud lightning, occur at stations protected by arresters. Although the two customer's stations giving the most trouble were only two and three miles from the sub-station, a gap of 0.4 in. between line and ground at the main sub-station would not spark over although the spark would jump 3.5 in. and more at the customer's sub-station. This is direct proof that the peak value of lightning potential is much higher at the point on the line nearest the cloud than elsewhere, and rapidly diminishes as the charge travels along the line, dragging its complementary opposite charge along the high resistance of the surface of the earth.

*Notes on choke-coils.* Twice during the tests the lightning choke-coils showed very materially their beneficial effect. On the line side of the choke-coils an arrester with a single gap length of about 1 in. was installed and another arrester with a gap length of about 0.5 in. on the station side, on the bus-bars. Two discharges occurred over the 1 in. gap which did not discharge over the 0.5 in. gap in spite of its lower sparking potential. The conclusion from the experience is that the discharge must have been of both high frequency and high potential and furthermore that the arrester discharged the lightning before the charge could pass through the standard lightning choke-coil.

That many discharges passed through the choke-coils to the 0.5 in. gap may be due to the conditions of lightning potential and frequency. If a lightning potential in the neighborhood of 1 in. gap equivalent and of moderately high frequency came into the station the choke-coil would allow the potential of the bus-bars to build up to a potential equivalent to 0.5 in. and then start the discharge over the arrester connected to the bus-bars. The aim in the design of choke-coils is to make them just large enough so that if the frequency of the discharge is not sufficient to pile up the potential in front of the choke-coil it is not high enough to injure the end turns of the transformer.

Once during the season a phenomenon occurred which seems to bear out further the experience of the laboratory that a choke-coil may, under certain circumstances, cause a longer spark after the discharge passes through it than it will on the line side.

The laboratory tests were described by the writer in the discussion at Niagara Falls last year. The equivalent effect occurred on the line. From the main sub-station two lines ran south and one north. Each carried a telephone circuit. The lightning recorder on the southern telephone circuits recorded a lightning stroke to the south but the lightning-arrester on the north power line discharged, although its single gap was approximately the same as the arrester on the south power line. In other words, the lightning seems to have passed through a choke-coil to the bus-bars and back through another choke-coil to the north arrester. The hole in the paper punctured by the static on the telephone lines indicated a discharge of medium quantity only. This experience carries only its face value and is not sufficient to be the basis of definite conclusion. A method will be outlined later for studying the operation of choke-coils on transmission lines, looking toward the procuring of definite data.

*Experiences with a grounded phase*. Several times during the season a phase was accidentally grounded. Each time there was an arc to ground and vicious surges occurred on the lines. Some of these were extremely odd. A lightning stroke came into the main sub-station on the 43,500-volt line. The lightning-arresters were designed with permanent resistance in series limiting the current to about 6 amperes at double normal potential; consequently the discharge took place between a phase wire in the station and an iron girder, some 18 in. distant. This arc roared continuously during the entire trouble. The liquid-electrode arresters on the 17,000-volt circuit discharged continuously for several minutes but were finally disconnected by their fuses as they had reached their limit of endurance. A switch broke down at Camp Bird Mill, throwing a ground and short-circuit on the 17,000-volt circuit. An arc jumped from each of two phases downward and out about 16 in. to insulator caps and across between caps 20 in. making a total of 52 in. Subsequently the arc rose on each side to the ceiling girders making a total of 6 ft. Meanwhile all the iron pipes and rods in the building were alive with brush discharge. The static from the iron pipe, carrying the 110-volt lighting wires, discharged against the white brick wall so viciously as to leave a permanent dark streak. The 110-volt light cables were short-circuited by induced sparks from the arcs on the high tension circuits. A spark jumped several inches from a pipe to the iron rod actuating a 2300-volt oil switch. The trouble was removed by opening the switches at the power house. Except the oil switch at Camp Bird no apparatus was damaged.

This trouble arose from the lack of a good lightning-arrester for transitory lightning. The secondary trouble was due to the lack of an arrester that had a long endurance for continuous surges. The cone-type aluminum arrester was not installed until later. To any witness of these phenomena there can be no doubt that the discharging of these continual surges is the most difficult problem in lightning protection.

*Another arcing ground.* The Champion mine had no protective apparatus installed. A stroke of lightning came in and damaged a 17,000-volt transformer bushing. Subsequently this transformer was thrown back into service on the 17,000-volt circuit for a minute. It arced over its bushing to its case. The case was insulated from the earth by wooden supports. The lightning-arresters in the main station did not discharge. Later the switch was closed for a little longer period with the same result. A third time the switch was closed, the case began to arc to ground and the lightning-arresters began to discharge continuously at the substation until the transformer was again disconnected.

*Subsequent arcing grounds.* Later in the season a cone-type aluminum arrester was installed on the bus-bars of the 17,000-volt system. A grounded phase occurred twice after this arrester was installed. The arrester discharged continuously for over 15 minutes, and relieved the line, until the ground was removed.

*Direct stroke.* The writer had planned to make a direct study of cloud lightning but, due to the time absorbed by the measurements on the line and an accident, Fig. 6, it had to be postponed. Indirect studies were made both on the line and in the laboratory. There are no overhead grounded wires on the Animas system. So far as practicable the lines are run along the bottoms of the cañons and gulches. The mountain sides are steep and give some protection, no doubt, against induced static. At many points the lines run exposed up the sides and over the ranges but by the law of chance all these points were uninjured, so far as known, except one. This happened on the 43,500-volt line about a mile away from the power house. At the power house, this line rises abruptly 1000 feet and is carried along a high plateau. At the point struck, five poles were more or less splintered, although none was rendered unserviceable, and incidentally, no apparatus was lost in the power house. Splinters were thrown edgewise out of the surface of the poles to a distance of thirty feet. The hole or groove was often less than ¼ in. wide but 1 in. or more deep. Along the line, quite near, with their tops higher than the wires, were several trees. The question arises, why should the lightning choose a path through the high insulation of the poles rather than strike the tall sappy trees of greater conductivity? The reason for this differentiation may possibly be due to chance but it seems to lie in the conductivity of the horizontal line relative to that of the earth and tree. As further evidence of this, two direct strokes occurred in this neighborhood a year before which scarred the poles and there was no tree damaged near the line.

It may be imagined that when a charge on a cloud begins to concentrate in a discharge path, the corresponding induced charge on the earth concentrates under the same point.

The potential at the tree top depends directly on how much static electricity can get to it through the relatively high resistance of the tree and earth. Although the line is not connected to the ground, it holds a considerable charge due to gradual leakage as the cloud moves over the line. This charge can concentrate with no impedance but the inductance of the line, and due to this concentration the excessive displacement current on the line may swing the cloud discharge into this path. Once the lightning strikes the line, the potential builds up too rapidly to be released by spreading the charge over the line and consequently it takes the shortest single path or multiple paths down the poles. The laboratory tests bearing on this theory are given below.

Many of the strokes of cloud lightning observed were between clouds and not to earth.

*Wooden versus metal cross-arms*. Under the heading of lightning potential the question was raised " does series resistance affect the spark potential of a needle-gap?" The answer was, that it affected it only slightly if the resistance was not carried too high. With a discharge current of half an ampere, there is no great change in the spark potential even for suddenly applied potentials of high frequency. When, however, the resistance in series with a gap is greatly increased, the current necessary to charge the static of the needle points and furnish the energy for the brush discharge which precedes a spark, is retarded and an equal gap in parallel having no series resistance will take the spark.

The same phenomenon occurs on transmission lines in differentiating between wooden cross-arms and metal cross-arms. If the wood is dry there is no question but that the insulation between the two line wires is greatly increased. On the other hand, if the wood is wet and dusty the value of the wooden cross-arm is not so evident. The following experiments were made to show that on low frequency, say 60 cycles, the wet wood gives no better insulation than the metal, but at high frequencies it gives much better insulation. A wooden cross-arm was arranged as shown in Fig. 19: two porcelain tubes held wires 1.7 in. above the surface of the wood and 10 in. apart. On the upper surface of the wood tin foil or a wet towel was placed in imitation of line conditions. Fig. 19 shows the conditions of the second test. The first test was made on a 60-cycle circuit with a needle-gap in parallel with the cross-arm. The voltage breakdown was the same whether the wet cloth or the metal was used. By transformation, the voltage was 46,900 (eight readings) and by needle gap it was 3.5 in. (52,000 volts by interpolation from the curve). This higher indicated potential by the latter was due to local oscillations set up by corona discharges over the porcelain top. After the cloth had dried out somewhat the spark potential by transformation rose about 2 per cent.

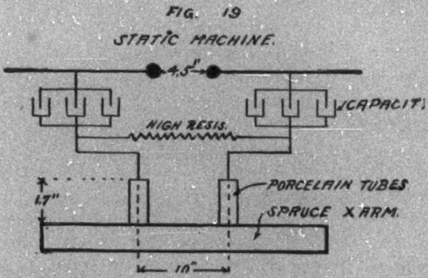

Fig. 19.—Diagram of connection for the laboratory test proving that the wooden cross-arm has great advantages over the iron cross-arm in resisting lightning strokes

The potential was then suddenly applied by means of the apparatus shown in Fig. 19. The frequency was 2.25 million cycles per second. The applied potential was a 4.5 in. gap between spheres 1.25 in. in diameter. The equivalent needle gap was 5.6 in. (68,000 volts) when the cloth was used very wet. The equivalent needle gap was only 2.5 in. (42,000 volts) when the metal plate was used between the porcelains. This disruptive voltage is even less than with the gradually applied potential. It results from the multigap effect of the metal plate. The plate has a static capacity which takes an appreciable charging current across the gaps. It is well to note that 5.6 in. was the limiting potential that the needle would spark over, so the actual conditions would have been even more favorable to the wet wood if the applied potential had been greater. Taking it as it was, the wet wooden cross-arm was 160 per cent. better than the metal as a protector against high frequency lightning and the metal cross-arm is only 80 to 90 per cent. as good for lightning as it is for generator potential.

Although these figures will, no doubt, be somewhat modified by changing the relative conditions of the test, it is safe to conclude that a wooden cross-arm is always to be recommended from the standpoint of insulation and would be a most desirable and economical feature even on iron towers. It is usually cheaper to add insulation with wooden cross-arms than it is to obtain it with added porcelain in the insulator. When the wooden cross-arms is only damp or dry it may add greatly to the insulation against lightning. These tests have a bearing on the use of insulator horn-gap protectors that will be apparent to the engineer.

## GENERAL COMMENTS ON THE ARRESTER EQUIPMENT OF THE ANIMAS COMPANY

Last summer the equipment of arresters consisted of four 43,500-volt special multigap arresters using concentrated series resistance, four 17,000-volt multigap arresters using distributed series resistance, and five liquid-electrode arresters. Two of the 17,000-volt arresters were rendered inoperative by having two liquid-electrode arresters installed in parallel. The liquid electrodes invariably took the heavy discharges. The following brief comments are made on the operation of the arresters during the season:

The series resistance in the high-tension arrester was of such value as to limit the dynamic current flow to six amperes at double normal voltage. The lightning strokes in this district were much too severe to be discharged at this limiting discharge rate, consequently three times during the season discharges took place between the station wiring and the girders, jumping 18 in. or more to ground. The 17,000-volt arresters with the series resistance limited the current discharge to 12 amperes, and usually were able to take the discharges. In one noteworthy exception, an arc took place between a lead-in wire and the ground. The liquid-electrode arrester on the 17,000-volt circuit gave satisfactory operation in all cases of transitory lightning, but during grounded-phase conditions the arrester continued to operate for some minutes until it was somewhat damaged. These arresters are not designed satisfactorily to take care of continual lightning, although they have an endurance that is several hundred or thousand times the endurance of the multigap arrester. If the entire system had had adequate protection against transitory lightning there would have been no trouble with recurrent surges, with but one exception—a direct stroke on the high-tension line. Since there are more than thirty points to be protected on the 17,000-volt system and only seven points protected, recurrent surges from failure of insulation at the unprotected stations occurred several times during the season and interruptions were caused by short-circuits as the result of sparks at unprotected stations. Additional arresters for the system were on order but arrived too late to be installed for the season of 1907.

The full protection of the system involves: first, the installation of one liquid-electrode arrester at the power house on 43,500 volts; secondly, one gap-aluminum arrester at the sub-station on the bus-bars, 43,500 volts; thirdly, three additional liquid-electrode arresters on the 17,000-volt circuit; fourthly, ten additional aluminum arresters on the 17,000-volt circuit; and, fifthly, completion by installation of reconstructed multigap arrester. The units of the multigap arrester formerly on the 43,500-volt circuits were utilized in the special design of arresters for the 17,000-volt circuit. By this change practically no money was lost in the lightning-arrester investment.

*Location of arresters.* The object to be obtained in the location of arresters to the best advantage is as follows:

Aluminum arresters should be distributed as uniformly as possible over the system, choosing the more important stations where there is an actual attendant, or one in the near neighborhood. These arresters should have their series gaps set at a comparatively low value in order to take care of recurrent surges from an accidentally grounded phase. The liquid electrode and multigap arresters at adjacent stations will require a higher abnormal potential to start the discharge and by proper proportioning should be protected against recurrent surges by the adjacent aluminum arresters. Recurrent surges have, in general, lower frequency than lightning from induced clouds and are not so much localized. Therefore the lightning-arrester designed for transitory lightning should discharge any induced cloud effects in its locality, but should pass on recurrent surges to the nearest aluminum arrester. In stations where there is no attendant, and none available within five minutes' call, the setting of the gap of the aluminum arrester should be such as to make its action transitory, except for exceedingly bad local conditions. In the main sub-station the aluminum arrester should have a gap setting only slightly above line potential with the object of making these arresters discharge, as far as possible, continuous lightning from outside points on the line. The object of this is twofold; first, to keep the line potential down; secondly, to draw the attention of the attendant to the fact that there is trouble on the line which must be located and corrected.

Since the aluminum arrester is designed to have a duration of discharge of a half-hour or more, this should give sufficient time to locate the particular circuit on which the trouble occurs and make the necessary switching without disturbing the rest of the system. It is evidently inadvisable to have any unattended aluminum arrester discharging surges which do not make themselves known to the station attendant, because the result would be final disconnection of the aluminum arrester from the circuit by the blowing of its series fuse, thus leaving the station without any protection whatsoever. After such an arrester is disconnected the surges will be carried on to the next arrester or into the sub-station. In localities where there are two or more stations near each other an endeavor should always be made to utilize a multigap arrester at one, and either an aluminum or liquid-electrode at the other. In this way even the multigap arrester of low discharge rate could be utilized, since the adjacent arrester of large discharge rate would assist in discharging the cloud lightning.

*Characteristics of the gap-aluminum arrester (concentric cone type). First.* The general characteristics of the aluminum cell with a definite limiting voltage, above which the current flows through freely, are known. At voltages above the critical value the film has no resistance and the only resistance in the circuit is the internal resistance of the electrolyte. In consequence of this characteristic the discharge rate at double normal voltage can be made as high as desirable.

*Secondly.* When the aluminum plate with its film-coated surface stands in the electrolyte, the film dissolves more or less rapidly according to the nature of the electrolyte. This dissolution can be made very small or considerable by the choice of the electrolyte.

The *third* feature in regard to the arrester is its endurance to continual lightning. The chief obstacle to the length of endurance is the same as in all other electrical apparatus; namely, heating; the arrester can be made to endure from a minute up to six months or longer by appropriate designs.

The *fourth* factor in the design of the arrester is its total life. The arrester should be given a life of several years. This is influenced by the nature of the electrolyte as well as the number of times and duration of the discharge.

The *fifth* factor entering into the design of the arrester is the cost. The four other factors can be made as nearly perfect as desired, but with the limiting value of cost the three first named factors are somewhat at variance with each other; for example, with the same arrester it is possible to give high current discharge rate and low dissolution of film, but in so doing the duration of the discharge will be diminished. On the other hand, the duration of discharge and the low value of dissolution of the film may be maintained, but the high rate of discharge sacrificed somewhat. In designing arresters the aim has been, in general, to meet the specific conditions imposed by recurrent surges on a system.

Until the development of the aluminum arrester there was no arrester which would take care of recurrent surges. This condition was one of the justifications for the use of a grounded neutral system. To meet the condition of recurrent surges requires a lightning-arrester that will discharge these surges for a time long enough for switching to be carried out to isolate the circuit on which the trouble takes place; meantime a repair man can be well on the way to the point where the damage has been done. A half-hour or an hour would usually be sufficient to do this. Therefore in the general design of the arrester to take care of recurrent surges the parts should be so proportioned as to give, first of all, the duration of discharge; secondly, the parts should be so proportioned as to give a discharge rate high enough to take care of any kind of induced or internal lightning. The value of this discharge rate is 1000 amperes at double voltage, correspondingly higher at triple voltage, and discharges all the way from 125 per cent. abnormal voltage, where the spark takes place, up to the highest voltage reached. In order to get this favorable condition, an electrolyte is chosen which is not the most favorable from the standpoint of dissolution of film; consequently in this arrester it becomes advisable to connect it occasionally to the circuit. In this matter there is a wide latitude of time; for example, it may be daily, or weekly, or even longer under the usual conditions of temperature. It has been found advisable, not only from the standpoint of the condition of the arrester, but also from the standpoint of the education of the operators, to recommend that these arresters be connected to the circuit at least once a day. To the writer's knowledge circuits have been shut down because the operator became frightened at the continuous discharge of the lightning-arrester when trouble occurred on the circuit. When continuous lightning occurs on the circuit it is desirable to have as long a duration of discharge of the arrester as possible. If the arrester has not been connected to the circuit for some time there is an initial rush of current which, although doing no harm to the arrester, warms it up unnecessarily and thereby shortens the possible time which the arrester would have operated had the film been in prime condition at the start. The wear due to this daily testing of the arrester is inappreciable and the time of the attendant is valuably spent.

When the aluminum arrester is to be used as a line arrester or in isolated stations where it is desired to take care of transitory lightning only it is necessary to make but two changes; first, a change in electrolyte to give less dissolution of film; secondly, as stated previously, the length of horn gap in series should be set at a value that will not be affected by the numerous surges of harmless abnormal potential which occur on transmission systems. Since the ordinary lightning-arrester does not begin to operate until at least double voltage is reached, and since practically all apparatus is tested at double voltage, it should be recommended that the gap of the line arrester be placed at not less than double voltage. It should be noted that if the arrester gives an initial current rush after being off the circuit for a long time, no harm will be done unless such initial rush of current should throw the circuit-breaker at the station. The slight amount of heating that occurs from this initial rush, lasting for not more than a very few cycles, and usually not more than one cycle, is negligible in the aluminum arrester used as a transitory lightning-arrester. This arrester may be allowed to stand for long intervals without connection to the line.

By sacrificing the duration of discharge, the arrester can be given a discharge rate of 2000 amperes at double normal voltage, simply by an increase in the amount of the electrolyte in the same set of aluminum cones.

To facilitate the testing of the aluminum arrester, the horn gaps are made in special form to act in three capacities: first, as a horn gap; secondly, as a short-circuiting switch to the gap, and thirdly, as a disconnecting switch.

### SOME AUXILIARIES TO THE GAP-ALUMINUM ARRESTER

*The lightning alarm and the fuse.* Since the duration of this type of aluminum arrester is limited, it is necessary to take steps to remove the trouble as soon after it occurs as possible. This arrester may be located either in-doors or out-doors; and in order to make sure that the operator's attention will be called to the condition of discharge, an extra cell is placed in the arrester circuit near the ground and leads are carried from there to the office of the attendant or the superintendent. This bell begins to ring as soon as the discharge takes place over the arrester and continues to ring until the arrester ceases to discharge.

The arrester has a definite endurance to the discharge. Actual tests have been carried on to determine the life of a 13,000-volt arrester under different conditions. The arrester was caused to discharge in relays of two or three hours twice a day until the total time was 80 hours. The arrester was then dis-assembled and it was found that the plates were somewhat worn but the arrester was still in good condition. If the duration of each relay had been less than two hours, the wear of the arrester would have been very much less. It is estimated, however, that the summation of the total time of grounded phases on a system would hardly reach the value of eighty hours in many years.

*Series fuses* in each leg are introduced to meet two conditions. First, if for any reason the dynamic potential should be increased to a dangerous value, the arrester will discharge these heavy currents continuously until disconnected from the circuit. It is evidently impossible to use these lightning-arresters to discharge high dynamic current for any great length of time. Under normal conditions the dynamic current reaches a value of 0.4 ampere on 25 cycles, and 1.0 ampere on 60 cycles. Any current above these values is current coming from lightning surges. This current does not represent directly an energy loss because the aluminum cell is a fairly efficient condenser and the power-factor is correspondingly low. When, however, the dynamic current for any untoward reason rises above the critical film voltage the current is entirely energy current and the internal loss considerable. In this discussion only energy from the generator is being considered, and it is evident to any operator that if the potential on his line rises to such an abnormal value for any length of time all the lights on the system will be burned out and the motors be operated under abnormal conditions. The second condition which may arise to necessitate the disconnecting of the arrester from the circuit will be that due to the length of time the arrester is discharging more than that recommended as the limit. It may be noted, although the time recommended is only a half hour or a little greater for duration of discharge, in actual practice, the arrester has been caused to discharge repeatedly for two or three hours at a time. If one of these arresters is placed on the circuit and left there the discharge rate remains about 1.0 ampere until the arrester reaches the limit of its endurance. This as already stated depends upon the heating. The current rises rapidly and if the arrester is not disconnected, one cell after another will short-circuit, throwing each time the extra potential on the other cells until finally the condition of total short-circuit is reached. These arcs will tear holes in the aluminum and will reduce the stack of cones to their scrap value. If, however, a fuse of size amply large enough to take any induced stroke of lightning be placed in series, the fuse will still be small enough to disconnect the arrester from the circuit in time to save it for future use. In either event, whether the arrester is disconnected by the fuse or is destroyed by dynamic current, this point of the system is left without protection, but by the use of a fuse the arrester in test has been put back into the circuit again with no material damage other than the natural wear due to the passage of current.

This matter of the use of a fuse in connection with the gap-aluminum arrester has been treated at some length in order to show the difference in this practise between the application to the aluminum arrester and the multigap arrester. There are some justifiable objections to a series fuse with the multigap arrester which do not apply to the aluminum arrester.

*Aluminum arresters for direct currents.* These arresters are applicable to pressures from 110 to 1200 volts. The form of the arrester differs from the gap-aluminum arrester. Containing jars are used to hold the greater quantity of electrolyte and give greater cooling surface. The characteristics of this arrester differ in some details from the cone type previously described. The direct-current arrester has no series gap. It is connected to the circuit directly and has a small leakage current flowing through it constantly. In consequence of having no series gap its dielectric-spark-lag is zero.

A brief review of the practical properties of the 600-volt direct-current arrester is given below:

There is no series gap. The normal leakage current is 0.001 ampere. The discharge rate at double voltage increases a million fold, it is 1000 amperes. Internal resistance above the *permanent critical voltage* is a fraction of an ohm. It may be frozen. Its inductive length of circuit is small. Its equivalent-needle-gap is 0.00 in. as compared to other types of arresters which give 0.25 in. to 0.58 in. under the same condition of test. Its measured static capacity is equal to over 400 miles of trolley wire.

*Temporary and permanent critical voltages.* A condition which may be designated as a temporary critical voltage of the film valves is prominent in this arrester. If an arrester is on a 600-volt circuit taking one milliampere of current and the voltage rises to a slightly greater value, say 625 volts, the current will suddenly rise to several amperes. If the voltage is maintained, a thicker film is formed which again reduces the current to a few thousandths. If the voltage decreases again, this extra thickness of film is re-dissolved. The *temporary critical voltage* of the film then is the constant running voltage. From another point of view, this statement is equivalent to saying that the arrester begins to discharge at a high rate of current the instant the voltage begins to rise. This is in contradistinction of all gap types of arresters which do not begin to discharge until the spark potential of the gap is reached. The *temporary* is to be distinguished from the *permanent critical voltage* of the film. If the voltage impressed on this arrester should rise to about 840 volts the limit of film formation is reached. Every volt pressure rise above this value causes an increase of current which is permanent so long as the voltage remains constant. This passage of current through the film should be carefully distinguished from the usual failure of a dielectric. For illustration, a thin layer of mica may have several thousand volts impressed upon it before it disrupts. This disruption will take place at one point and the voltage will drop to about 50 volts which is the ordinary arc voltage. The aluminum film does not function this way. The exact physical phenomenon is obscure, but it is evident that there is no analogous drop of potential at the film when the heavy current discharges and furthermore the current is distributed over the entire surface.

The nature of the film varies with the electrolyte. As a working hypothesis it is assumed that it consists of pure gases in a liquid form held in a hard insoluble skeleton of aluminum hydroxide. This is borne out by most of the observed phenomena and so far as known is not disproved by any.

### EARTH CONNECTIONS

The ohmic value of the earth resistance in connection with protective apparatus is usually unknown. The usual directions for making an earth connection are one or more of the following.

*a*. Bury a slab of copper about two feet square in coke.

*b*. Connect a wire to the water mains.

*c*. Locate a copper plate in the mud of a body of water.

The first is expensive to install, is concentrated at one point, and has an unknown value of resistance which may vary greatly from a change in moisture. The second gives a low value of resistance as a rule but is not available on lines and in many sub-stations. The third may give a low resistance but usually has an objectionably long earth connection.

With the object of learning the effect of distance between earths on the ohmic resistance, effect of the size of the earth plate, depth of conducting stratum and the most economical method of reaching it and maintaining contact, the writer has made a series of tests, several of which are given below. Some of these tests were begun in 1906 and continued to the present.

*Methods*. The first consideration was the choice of a method of test. The method employing the Wheatstone bridge recommended in some publications on telegraphy is unsatisfactory on account of the counter electromotive force of contacts. The simplest test is the measurement of voltage and current at the convenient value of 110 volts impressed and the only question regarding this test was the choice between alternating and direct currents. Alternating currents gave the most satisfactory results. If one volt counter electromotive force was subtracted from the impressed direct voltage the same resistance was obtained as given by alternating currents, except in one case. In this case the iron pipe was driven vertically through a deposit of coal ashes and cinders. At 1 ft. depth the direct-current method gave a resistance of 36 ohms whereas the alternating-current gave a resistance of 26 ohms. Since this deposit of cinders and ashes was not thick, its relative effect disappeared at a greater length of pipe. At a depth of 8 ft. the values by alternating and direct current sensibly coincided. This difference in resistance seems to have been due to some effect analogous to that in a coherer. The 110 volts of alternating current were obtained by transformation from 2300 volts; the high-potential static came through the particular transformer so badly as to make the handling of a low-voltage wire exceedingly disagreeable. This high potential may have caused the particles to cohere. The direct current was taken from a battery.

In all tests 1-in. iron pipes were used. The lettered pipes were 5 ft. and the numbered pipes 8 ft. in the ground. The resistances were measured between each pipe and the water-pipe main and also between earth pipes. The resistance of the water-pipe main was 3.3 ohms. The resistance of the earth pipes varied from 10 ohms to over 1000, according to the condition of the earth.

Fig. 20 shows the location of the earth pipes; numbers 1, 2, 7, 9, 3, 8, and 5 are on the same level in wet or moist ground. No. 4 is in a pine grove on an upper terrace eight feet above in dry earth and No. 6 is on a terrace ten feet below in very wet earth. The distances between earths: from 2 to 7 is 5 in. (probably not accurate to 8 ft. depth), 7 to 9 is 1.6 ft., 9 to 3 is 4.75 ft., 2 to 3 is 6.5 ft., 2 to 8 is 33 ft., 2 to 9 is 1.9 ft., 3 to 7 is 6 ft., 2 to 5 or 6 is 650 ft. Pipe earths *B*, *C*, *D*, *E*, and *F* were given special treatment to increase the conductivity of the earth near them.

*Resistance per foot depth of pipe.* The curves, Fig. 21, show the resistance of each earth pipe at each increase of one foot depth. The water main is designated as *G*. *G*-1 means that the two are used as electrodes. The first measurement taken was with the

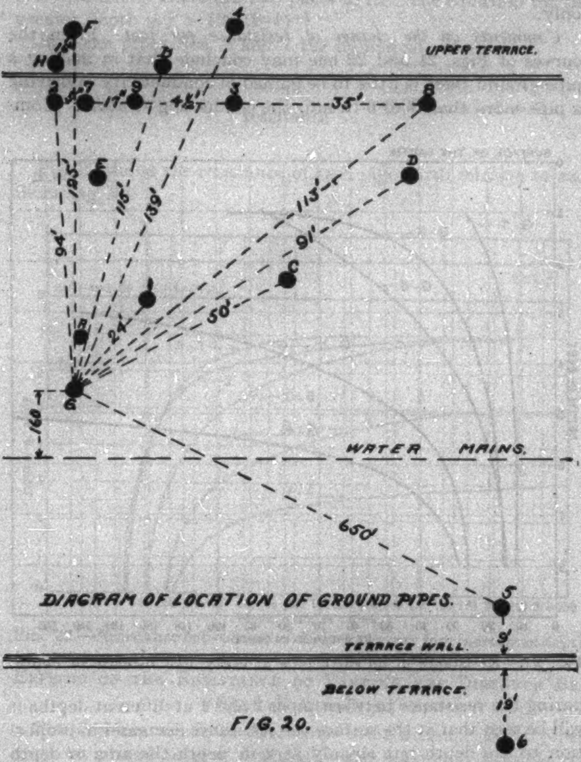
F
16'
H
4
D
UPPER TERRACE.
2
7
9
3
8
17'
4½'
35'
E
D
125'
115'
139'
113'
91'
94'
C
1
50'
A
24'
G
160'
WATER MAINS.
650'
DIAGRAM OF LOCATION OF GROUND PIPES.
5
9'
TERRACE WALL.
BELOW TERRACE.
19'
FIG. 20.
6

Fig. 20.—Map of earth pipes at the laboratory

pipe resting on the surface of the earth. The resistances of these various connections varied from 1000 to 8000 ohms and cannot be shown on the scale of the print. The curves show that pipe No. 1 was well into the conducting stratum at 1 ft.

depth; Nos. 2 and 3 at about 2 ft. depth; No. 6 below the wall at about 3 ft. and No. 4 on the dry upper terrace had to be driven about 7 ft. before it penetrated the conducting stratum. No. 5 at 8 ft. depth is equal in resistance to No. 1 at 1 ft. depth only.

*Comments on the change of resistance per foot.* From the curves of Figs. 21 and 22 one may conclude that in making a pipe ground there is little to be gained in conductivity in driving a pipe more than 3 to 6 ft. into the conducting stratum. Comparing the resistance between pipes 2 and 1 at different depths it will be seen that at the surface the resistance decreases in proportion to the depth but already at 2 ft. depth the area or depth is increased 100 per cent. over 1 ft. yet the resistance decreases only 46 per cent. The ratio of these percentages is roughly 2½. Between 7 and 8 ft. the area increases 14 per cent. but the resistance decreases only 3.4 per cent. The ratio of these percentages is roughly 4. In other terms the resistance is only decreasing one-fourth as much as the area is increasing. In fact this curve

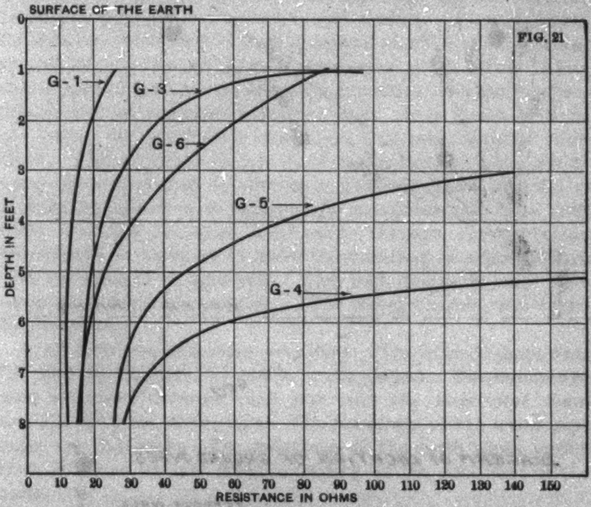

FIG. 21.—Resistance of an earth pipe at every foot increase in depth.

is logarithmic and theoretically nearly reaches zero resistance when the pipe is infinitely long. Since the specific resistance of the earth varies with the depth the equation of the curve is not simple. There are two parts to it. The equation for the greater depth is $f = 100\,(k-b)^{A}$

Between pipes Nos. 2 and 1 the numerical values are:

$$f = \text{feet depth},\ k = \frac{1}{\text{resistance}},\ b = 0.0035 \text{ and } A = 2.$$

Fig. 22 shows the resistance of each pipe earth relative to and including No. 2.

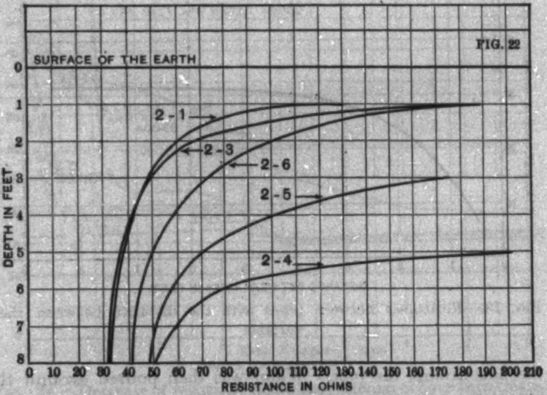

Fig. 22.—Resistance between pairs of pipes at every foot increase in depth

## Effects on the Resistance of Varying the Distance Between Earth Pipes

The desideratum is to determine what distance apart pipes must be placed to give practically the maximum possible resistance. It is a well known fact that after a certain distance between earths is reached any further increase in distance will not increase the resistance between them. Fig. 23 shows the resistance taken between pipes set at various distances. The resistance reaches a nearly constant value at about 6 ft. separation. Therefore if it is desired to place a ground resistance in series between phase and phase of a line as suggested by Dr. C. P. Steinmetz some years ago, it is necessary to separate the ground pipes only by this distance. In other words it is not necessary to make one at one pole and another at the next pole.

*Treatment to improve earths.* The material of the earth in this locality seems to be a mixture of clay and sand. Five pipes having a length of 5 ft. each were used in this test and are designated by the letters *B*, *C*, *D*, *E*, and *H*. The variable resistance of each of these earths relative to time, is shown in Fig. 24. Tests were made for eight consecutive days.

Earth *B* was made by digging a post hole and mixing the dry earth with 16 pounds of salt and pressing the mixture back into the hole around the pipe. Water was then poured around the top of the hole. This pipe was located on a projection of the terrace, 8 ft. high, so that there was a sudden drop on one side of 8 ft. and on the other side a drop of 4 ft., to a ditch. The resistance of the earth decreased daily showing that the salt water was percolating from the dry earth of the knoll down to a conducting stratum about 3 ft. below the pipe. During the eight days water was poured onto the top of this earth four times. It has now stood one year and seven months and the ohmic resistance has not varied materially.

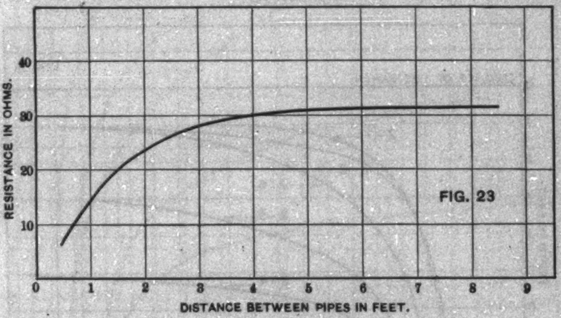

FIG. 23.—Resistance between pipes with the distance between them variable

Earth *C* was made by digging a post hole, pouring into this hole sixty pounds of lime, sixty gallons of water, and filling in with dirt around the pipe. The location of this earth was below the terrace in good ground. Earth *C* is located quite near the previous mentioned earths designated as 2, 7, 9, and 3, and this treatment added nothing to the conductivity of the already moist earth.

Earth *D* was formed by simply driving a pipe 5 ft. into the earth, cupping out around the pipe at the top. Four pounds of salt were then placed in this cup and water was added. Twice subsequently, water was added. Results are shown by the curve.

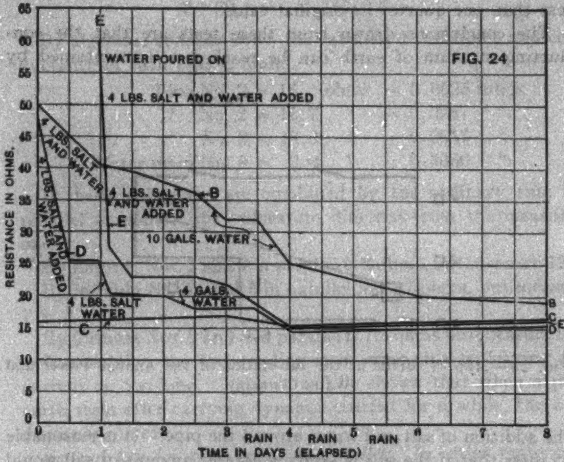

FIG. 24.—Decrease of resistance versus time after pipes have been treated with salt water

Earth *E* was formed by laying a pipe on the level ground and covering with earth. Salt was then scattered over the earth and water poured on the mound. In this case fairly good conductance was obtained 1 ft. below the surface. This fact is indicated in the curve sheet by the sudden drop in the resistance from 60 ohms to 26 ohms during the same day.

Earth *H* was formed by laying a pipe horizontally in a shallow ditch and covering with earth. Fourteen pounds of salt were mixed with the earth and then water poured over all. This earth was located on the edge of the upper terrace which is 8 ft.

high. The initial resistance before water was added was 545 ohms. After two and one-half gallons of water were added, the resistance dropped the same day to 87 ohms. Water was added each subsequent day and after six days the resistance had gradually dropped to 25 ohms, (these results are not shown in Fig. 24). They are most remarkable, however, in that the salt solution had to percolate about 8 ft. before it struck a stratum of good conductivity. After one year and seven months the rain has washed out some of the salt from the covering of dirt about one inch deep, and the resistance has risen, but it is still less than one-quarter its original value.

The conclusions drawn from these tests are that the conducting stratum of earth can be reached and maintained by the addition of salt and water around the pipe. It is reasonable to infer that if the soil is sandy a greater amount of salt would have to be added. The salt in itself is hygroscopic and will always retain a certain percentage of moisture. In localities where the rain washes the salt through to the conducting stratum rapidly, it will be advisable to add salt at least once a year.

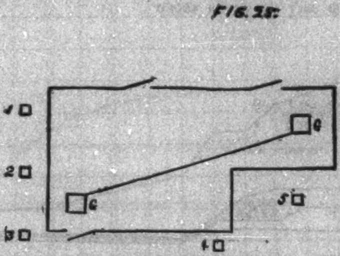

FIG. 25.—Map of earths at the sub-station of the Animas Power and Water Company

*Multiple pipe earth connections.* The same set of pipes (2, 9, 7, 3, and 8) used to obtain the variation of resistance with the distance between electrodes, was also used to get the variation in resistance, by putting the different ones in parallel. Numbers 2 and 7 were driven 5 in. apart. There is no material variation in the resistance of these two earths, whether multiple or singly—the value is about 16 ohms to the water main. If, however, No. 2 is combined with No. 3, which is 6.8 ft. away in a line parallel to the water main, the resistance of the two in multiple is only 10.7 ohms. The data are:

$G+(2)$ = 16 ohms.
$G+(7)$ = 15.9 "
$G+(2, 7)$ = 16 "
$G+(3)$ = 19.3 "
$G+(2, 3)$ = 10.7 "
$G+(8)$ = 21.6 "
$G+(2, 8)$ = 9.8 "
2+(3) = 28.7 "
2+(7) = 0.755 "

By algebraic combinations, the calculated resistance and conductance of each pipe is found.

Pipe No. 3 = 16 ohms = 0.0625 mhos
" No. 2 = 12.7 " = 0.0787 "
" No. 8 = 18.3 " = 0.0547 "
Water main No. 9 = 3.3 " = 0.3030 "

If these resistances are combined by the ordinary rule for parallel resistance, the values are different from the measured ones.

By formula Nos. 2 and 7 in parallel is 8 ohms, but measure 12.7.

By formula Nos. 2 and 3 in parallel is 7.07 ohms, but measure 7.4.

By formula Nos. 2 and 8 in parallel is 7.5 ohms but measure 6.5.

Incidentally, the last reading is in error due to leaving the current on too long. Later it will be shown that when a pipe earth rests after carrying dynamic current for a while, the conductance increases.

*General law for pipe earths in parallel.* In order materially to reduce the resistance of a pipe earth by additional electrodes, the added pipe must be driven out of the denser stream lines of current of the pipes already driven. As example, No. 7 was driven in the dense stream lines of No. 2 and did not lower the resistance by a measurable value whereas No. 3 was pretty well out of the stream lines and nearly follows the well known laws of paralleling resistances. Figs. 26, 27, 28, and 29, show the stream lines for various conditions; Fig. 26, vertical pipe and water main; Fig. 27, horizontal current lines between two vertical pipes; Fig. 28, roughly the vertical cross section of current stream lines between two pipes partially driven. The two logarithmic factors are represented, one by the straight lines and the other by the curved lines—Fig. 29, current stream lines of a pipe touching the surface. The similarity of these current lines to the static field around a charged conductor is evident, in fact if the earth is assumed to have uniform resistivity, the laws are almost identical. As an example of the relation, the capacity of a single conductor 0.18-in. diameter and 75 in. from the earth is 0.0169 microfarads and the capacity of a conductor twice the diameter is only 0.0195 microfarads; in other words, an increase in size of 100 per cent. increased the dielectric displacement current only 15 per cent. If the earth pipe is driven several feet to minimize the proportional effect of the tip and lines represented in Fig. 29, the same law should hold approximately true for dynamic current as for displacement current; consequently with one earth pipe resistance known, the resistance of

FIG 26

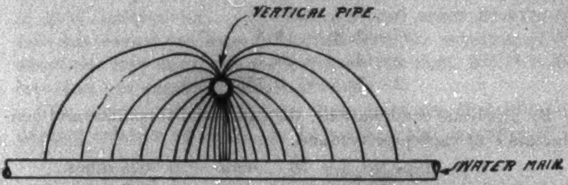

FIG. 26.—Current stream lines between a vertical earth pipe and a horizontal water main. They are similar in form to a static field

FIG. 27

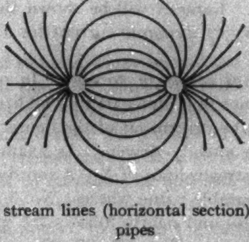

FIG. 27.—Current stream lines (horizontal section) between two vertical pipes

a pipe of different diameter may be estimated from appropriate tables of static capacity. Returning to the static analogy, if another line wire 0.18 in. diameter is strung parallel to the first at a distance of a few feet, the capacity of the two in parallel is twice 0.0169 microfarads. Analagously, the conductance of two earth pipes is increased.

Values of resistance of the condition of the pipe touching the surface (Fig. 29) are herewith given on account of their relation to a broken line wire touching the ground. Pipe No. 1 was 1200 ohms, No. 2 was 1260 ohms and No. 4 was 6000 ohms.

FIG. 28.

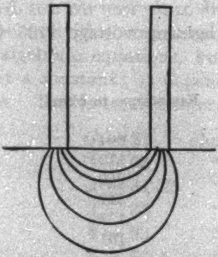

Fig. 28.—Current stream lines (vertical section) between two vertical pipes touching the surface of the ground

FIG. 28a

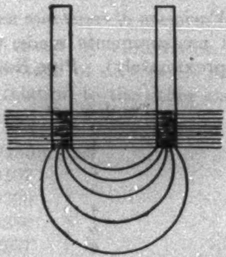

Fig. 28 a.—Current stream lines (vertical section) between two earth-pipes partially driven. The two sets of lines represent the two logarithmic factors of the equation of the resistance

In connection with the subject, the drying out of the earth by dynamic current as given later should be noted.

*Animas earth tests.* These tests of earths around the laboratory were supplemented by measurements of earths on the Animas Power and Water Company's system. Fig. 25 is a map showing the location of the earths at the sub-station near Silverton. The ground in this locality is principally the gravel washed down from the steep mountain sides. The Animas River flows past the sub-station at a distance of about 100 yards. Under the station floor at the two points shown are two of the old type grounds consisting of expensive copper plates buried in coke. These two together are designated as *G* in the notes. Around the building five iron rods were driven to a depth of 6 ft. entailing unusual trouble on account of the stones encountered. The tests are divided into six parts.

1. *Variation of resistance with depth (dry earth).*
2. *Variation of resistance with time after salting.*
3. *Measurements of resistance between pipes in variable multiple groups.*
4. *Measurements of resistance between the sub-station and Hobbs' Switch,* 5.5 *miles up Gladstone Canon.*
5. *Measurement of resistance between sub-station and power house* 25 *miles down the Animas River.*
6. *Measurements of resistance of tree earth, pole earth, railroad earth, and side hill earth.*

*Variation of resistance with the depth as the iron rod was driven.* All measurements made with the lighting voltage (125 volts approximately). Pipe No. 3.

| Depth in feet | Resistance in ohms |
|---|---|
| 1 | 604 |
| 2 | 172 |
| 3 | 250 |
| 4 | 312 |
| 5 | 125 |
| 6 | 161 |

The irregular variations are due to the lateral displacement of the iron rod as it pushed by some obstructing stone.

*Time resistance variation after salting the rod at the surface of the ground.*

| Time in minutes | Resistance in ohms |
|---|---|
| 0 | 161 |
| 5 | 62.5 |
| 10 | 47.7 |
| 30 | 38.5 |
| 360 | 33 |

This earth was located at the corner where all the rain water from the roof was carried. A storm occurred and considerable water was discharged around the pipe. Enough of the salt was washed through the gravel to raise the resistance from 33 to 35 ohms. The other earths were unaffected by the rains.

*Measurements of resistance between pipes and various multiple groups.*

| Earth pipes | Resistance in ohms | Pipes in multiple | Resistance in ohms |
|---|---|---|---|
| 1 to 3 | 128 | *G* to 1, 2, 3, 4, 5, | 32.3 |
| 2 to 3 | 64 | *G* to 1, 2, 4, 5, | 36.6 |
| 4 to 3 | 128 | *G* to 1, 2, 3, 4, | 35. |
| 4 to 3 | 115 | *G* to 1, 2, 3, | 37.1 |
| 3 to 5 | 107 | *G* to 1, 2, | 47.4 |
| *G* to 5 | 85 | *G* to 1, 5, | 58.2 |
| *G* to 1 | 115 | *G* to 1, 3, 5, | 39.4 |
| *G* to 2 | 55.5 | *G* to 2, 3, | 39.4 |
| *G* to 3 | 57. | | |

The individual resistances can be found by elimination in the algebraic equations, but the resistance of any earth pipe is not a constant; it depends on its relation to the other electrode. This is treated later. The values calculated are:

$G = 22$ ohms $= 0.0455$ mhos.
$1 = 93$ " $= 0.0107$ "
$2 = 31.25$ " $= 0.0320$ "
$3 = 35$ " $= 0.0286$ "
$4 = 93$ " $= 0.0107$ "
$5 = 67.5$ " $= 0.0148$ "

By summation of the reciprocals the calculated values of resistances of the pipes in various combinations are:

1, 2, 3, 4, 5, = 10.3 ohms = 0.0968 mhos, *G* by subtraction from tests = 22
1, 2, 4, 5, = 14.7 " = 0.0682 " " " " " " = 22
1, 2, 3, 4, = 12.2 " = 0.0820 " " " " " " = 22.8
1, 2, 3, = 14. " = 0.0713 " " " " " " = 23.
1, 2, = 23.5 " = 0.0427 " " " " " " = 23.9
1, 5, = 39.2 " = 0.0255 " " " " " " = 19.

1, 3, 5, = 18.5 " = 0.0541 " " " " " " = 21.

2, 3, = 16.5 " = 0.0606 " " " " " " = 22.9

Two salient features of these tests are: first, the low total resistance of the five pipes in parallel (10.3 ohms) as compared with the two station earths (22 ohms); second, the low cost and the easy and certain maintenance of the pipe earths as compared to the old type earths. The pipe earths are to be preferred, from every point of view.

*Measurements of resistance between the substation and Hobbs' switch, 5.5 miles up Gladstone Canon.* Three earths were made at Hobbs' switch and by means of the telephone wire connections were made between these earths and the earth ($G$) at the sub-station. No suitable measuring instrument was at hand so a voltmeter was used. The results are less accurate than the previous tests. In calculating the individual earth resistance the assumption was made that each earth carried a local value of resistance and that the rest of the resistance was in the main body of the earth between, or since there are mountains of granite in direct line between the two stations, that there was a resistance of the surface of the earth down one cañon to the fork and up the other, quite distinct from the local resistance. The calculated results seem to justify the assumption in this particular case. The Hobbs' earths were not salted and were made in ground through which snow water was percolating, consequently their resistances are high. The following values were obtained: Hobbs No. 1-437 ohms; Hobbs No. 2-100 ohms; Hobbs No. 3 (ground for telephone) 189 ohms; and the resistance of the telephone wire plus the 5.5 miles of earth between stations was 89 ohms. Subtracting the telephone wire resistance leaves the 5.5 miles of earth 36 ohms. The resistance to a lightning discharge passing along the wires cannot be less than this and is probably much greater.

*Measurement of earth resistance between the sub-station and the power house, 25 miles down the Animas River.* The total resistance, including both station grounds, the earth between and the line wire, was 55 ohms. The resistance of the power house earth plus the main body of earth was only about 30 ohms which is less than the main body of the earth to Hobbs' switch.

*Measurement of the resistance of tree earth, side hill pipe earth, pole earth and railroad earth.* Up on the gravelly hill side about 100 ft. above the substation was an evergeen tree. A line of nails was driven into the tree just above the ground and wired together. Six feet higher another set of nails was driven. The tree at the base is 5 ft. in circumference and at 6 ft. up is 4 ft. in circumference. Resistance of the base of the tree to station earth is 770 ohms and from the point 6 ft. up is 2820. Resistance per foot height of tree 340 ohms. An iron pipe driven 5 ft. near the tree measured 353 ohms dry and 190 ohms a short time after it had been salted down and wet with a bucket of water.

Seven nails four inches long were driven around the circumference of a spruce transmission pole just above the ground.

The pole stood on a level with the sub-station. The resistance to the sub-station earth was 1290 ohms; 14 in. higher up it was 3300 ohms. Seven more nails were driven at the same height to increase the area of contact. The resistance from the ground surface dropped to 980 ohms and correspondingly at 14 in. up it dropped to 2700 ohms. This gives about 1450 ohms per foot. At 6 ft. up, however, the pole was so dry that its resistance was

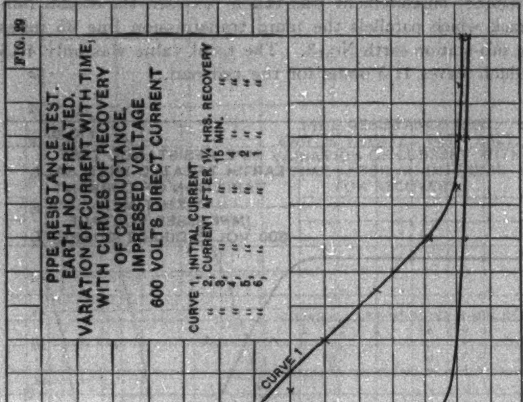

Fig. 29.—Curves showing the energy capacity of earth pipes, also curves of recovery of conductance
Earth not treated

too high to measure with a voltmeter having a scale of 150 volts and an internal resistance of 5200 ohms. The low resistance at 14 in. up shows the effect of capillary attraction in drawing up the moisture from the ground.

A resistance measurement was taken between the steam railroad track which parallels the main transmission line 35 miles and the sub-station earth No. 3. The total value was only 46.5 ohms which leaves 11.5 ohms for the railroad.

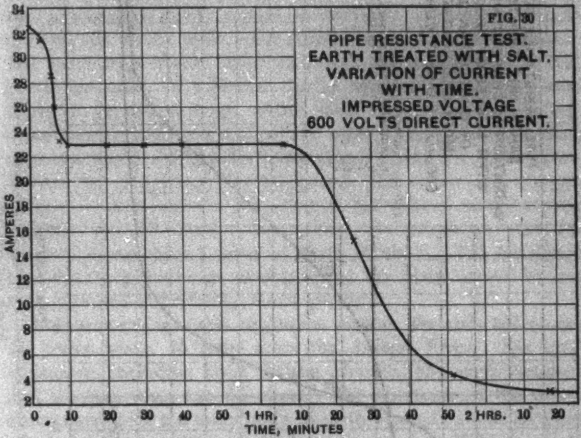

FIG. 30.—Curve showing the energy capacity of the same earth pipe salted

## EARTHS CARRYING DYNAMIC CURRENT

*Variation of earth contact resistance when dynamic energy is applied.* Occasionally dynamic energy is passed through the earth connection. This may occur: first, when arresters connected to different earths operate simultaneously; secondly, when a phase of a grounded neutral system is accidentally grounded; thirdly, to a less degree, when a phase of a non-grounded neutral system is accidentally grounded; and fourthly, when single-phase arresters are used connected to different earths.

A study of the effect of dynamic energy was made on pipe earth No. 1 near the laboratory, under the two conditions of unsalted and salted. The pipe was 1.25 in. outside diameter (known as inch pipe) driven to a depth of 8 ft. 600 volts direct current potential were impressed. The results are shown in the three curve sheets Figs. 29, 30, and 31. Fig. 29 gives curve of the unsalted earth and Figs. 30 and 31 of the salted earth.

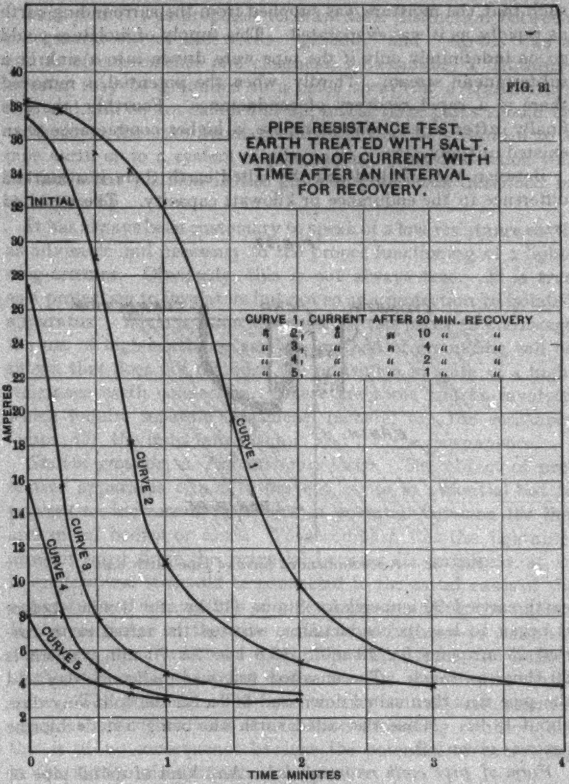

Fig. 31.—Curves of recovery of conductance of the same salted earth-pipe

The characteristic behavior was the same. At first there was a fairly steady current flow until the temperature increased sufficiently to make the pipe steam and boil away the moisture, then secondly, a rapid drop of current to a fairly constant value such that the moisture was supplied from the surrounding earth as rapidly as it was evaporated. This supply of moisture could go on indefinitely only if the pipe were driven into a sink or a subterranean stream. Thirdly, when the potential is removed there is a rapid recovery of conductance. Fourthly, there is finally, after a few minutes repose, a higher conductance than existed initially.

Between the unsalted and the salted earth there is a marked difference in the endurance or kilowatt capacity. The unsalted earth carried 20 amperes for 3 min. (12 kw. for 3 min.) before it began to lose its conductance, whereas the salted earth carried 23 amperes for 70 min. (13.8 kw. for 70 min.) which is 20 times as much. The unsalted test was made one day and the pipe was then salted down and left until the following day, about 18 hr. While the salted earth was being tested chlorine gas was given off.

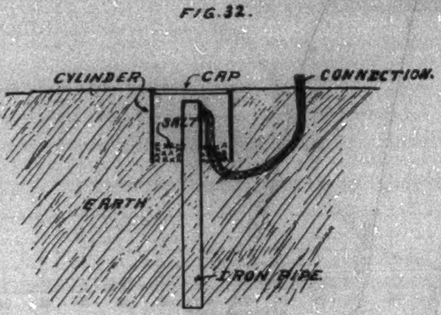

FIG. 32.—A recommended form of pipe earth unit

*Form of pipe earth recommended.* Any kind of metal pipe or rod driven into the earth a few feet makes a good earth connection if the soil around the pipe at the surface is cupped out, filled with a few pounds of salt, and water added. A neater form of earth unit is shown in Fig. 32. A cylinder of metal or earthenware of any available diameter is set around the pipe at the surface of the ground and covered by a lid. This receptacle will hold the salt. Its advantages lie in the easy inspection of the connection and protection of surrounding vegetation from the saline water.

Last year it was proposed to draw some distinction between the general use of the words "ground" and "earths" as a matter of convenience and clearness; for example, a lightning-arrester may be grounded to a cable sheath or a transformer case and still be not earthed at all, unless these parts should be earthed; on the other hand, the arrester may be grounded to a pipe earth or to a system of pipe earths. This distinction will be somewhat justified in the grounding methods described in the following.

It has always been customary to speak of a low-resistance earth as advisable and necessary to the proper functioning of a lightning-arrester. Obviously, this is not always true. It is true as a protection to insulators but not so as a protection to isolated apparatus. While it is not the object of this paper to encourage the use of high-resistance earth, a method of grounding will be shown that does not diminish the protection in spite of a high-resistance earth connection. There are three factors involved which require separate treatment; namely, (*a*), the resistance factor; (*b*), the inductance factor; and (*c*), the permanence.

*Station grounds. a. The resistance factor.* The object of protective apparatus is not to prevent a rise in potential but to prevent an increase in difference of potential between the line and metal bodies or cases. To accomplish this the lightning-arrester must limit the potential between its terminals; at its lower terminal it should be connected to the metal cases of the apparatus and to a system of pipe earths encircling the station. If the resistance of the pipe earths is so high as to limit the discharge, there will be a drop of potential from the outside of the station to the point under the line whence the charge came. The potential of the station may actually rise momentarily thousands of volts above the surrounding country, but this is of no consequence because the potential of everything in the station rises simultaneously.

There is one source of danger which should be avoided. If a water main runs into the station it should be connected to the multiple pipe earth, because if its resistance is low compared with that of the pipe earth a person could get a shock from a charge passing from the station into the water main. If it were not for the danger of the water main, a fairly high resistance of multiple pipe-earths would be advantageous in using up the energy of the lightning stroke without risk of the $I\,R$ drop causing a dangerous difference of potential. In isolated stations where there is nothing corresponding to a water main, multiple pipe earths around the building connected to the transformer cases should be sufficient. That is to say, a long lead running to the mud of an adjacent stream is needless.

The bearing earth connection resistance has on the protection of insulators, so far as known, may be theoretically explained. The only protection there is for an insulator is a lightning-arrester placed in the region of induced static from the clouds. The station arrester acts as a protection to insulators only when the inducing cloud is over the station. If the resistance of the multiple pipe earth is high it will, in the latter case, give theoretically a somewhat less protection to the neighboring insulators. Since salted multiple pipe earths, even under the very worst conditions, give lower resistance than the old method earth, there is no choice between them.

*b. The inductance factor of earth connections.* Since the resistance factor is brought to a matter of indifference by the multiple pipe earths, the inductance factor should be considered. It was feared that the iron pipe would offer greater inductance to high frequency currents than copper wire. Dr. C. P. Steinmetz has made calculations which show that the pipe is actually a better conductor of high frequencies than a large copper wire. Regarding the connections between a lightning-arrester and earth the rule has always been to make it as short as possible. It is advisable to drive a pipe earth directly underneath the arrester even if such earth must be of relatively high resistance. This earth should be connected to the other earths. A more general rule is: make the circuit between the line and earth through the arrester short relative to the length around through the apparatus to the earth. A choke-coil gives considerable added length. While this precaution may not be followed rigidly in high-tension apparatus, it seems to be extremely important in low-tension apparatus, especially with railway motors. Double-cotton-covered wire is delicate insulation. Some concrete ideas of what is possible if a storm cloud is over a trolley line may be gleaned from laboratory tests. With two leyden jars of the gallon size, giving a frequency of about two million cycles per second and a momentary current rush estimated at

1000 amperes, the potential drop along one foot of No. 10 B. S. wire will puncture the insulation between two wires, each double-cotton-covered; that is, four layers of cotton covering. The shortening down of the lightning-arrester circuit to the last possible inch may seem over cautious. With the old types of lightning-arresters which contain an appreciable internal resistance it is needless precaution, but the new aluminum arrester for railway circuits has an equivalent-needle-gap of 0.00 inches, an inductive circuit of only a few inches, internal resistance of only a fraction of an ohm, no series gap and a discharge rate of over 1000 amperes at double line voltage. Its normal leakage current is only about one millionth of this or 0.001 ampere.

While this arrester is designed to take care of the severest induced strokes it cannot of course prevent a drop of potential along its connecting lead. The ideal connection of this arrester to a trolley car consists in a lead carried from the trolley down near the motor or truck frame, connected to the lightning-arrester, and then carried back, not in the same conduit, to the car wiring. Nearly all the types of car wiring give this condition with varying degrees of perfection. While in most localities the lightning troubles encountered may not warrant the expense of rewiring, it is important to examine these features when the aluminum arrester is used in localities where the lightning is especially severe and frequent.

So far, only the length of lead has been considered. It is sometimes impossible to shorten a lead below a given length and still important to reduce the impedance of it. Since the smallest wire that will carry the dynamic discharge of an arrester has a negligible ohmic resistance, the shape of the conductor only need be considered. Theoretically, the inductance decreases nearly in proportion to the increase in metallic surface.* The equivalent-needle-gap, however, shows a less gain as the surface increases. The following measurements give relative concrete values of potential drop under nearly the same condition as that noted just above. A 5 ft. length of copper ribbon 2.5 in. wide and thin as paper was connected in series with an equal length of No. 10 B. & S. wire. The equivalent-needle-gap of the strip was $\frac{3}{16}$ in. (0.476 cm.) and of the wire $\frac{7}{16}$ in. (1.11 cm.). The potentials corresponding to these values of needle-gap are 3760 volts and 8750 volts effective—about two and one-fourth times as great. Using peak values, the potential drop per foot along the wire was 2470 volts.

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* C. P. Steinmetz and K. Ogura, "Inductance of Straight Conductors".

From the known data a value of current may be obtained by substituting in the equation $E = L\omega I$. The frequency was two and one-quarter million cycles per second, consequently the current must have been greater than 550 amperes. A partial check on this value may be made by assuming zero resistance and calculating the current by the previously given equation involving the total circuit.

$$I = V\sqrt{\frac{C}{L}}$$

By this equation the maximum possible momentary value of current in this circuit is 3000 amperes at 100,000 volts impressed potential.

The foregoing calculations indicate that a discharge of current and frequency so high will tax both the resistance and the inductance limitations of an arrester to the utmost. The practical question yet to be answered is when and how often may these conditions arise? A speculation is useful to the observer and student of this phenomenon.

First of all the conditions may be obtained when a direct stroke hits the line; but such a discharge does not, in general, reach the lightning-arrester. It is probable that it may happen to a degree when a car or station is underneath a thunder cloud which discharges to the earth. It seems quite certain that it cannot happen from a traveling wave along the line because of the relative valve of the inductance of the line to the capacity. It seems safe to presume that the combination of high frequency and large current occurs infrequently at an arrester.

*The permanence factor of earths.* The permanence of the conductance depends on the moisture. Tests have been made using 600 volts on a pipe earth to drive out the moisture. In this case there was no baking of the material surrounding the pipe and consequently there was a quick recovery of conductance. No tests with more power and higher voltage have been made and possibly a more lasting effect might be produced by a grounded phase on a grounded neutral system. If such occurred during a storm the multiple pipe earths would be especially valuable.

*Lightning conductors for the protection of buildings.* The customary lightning conductor is usually connected to a single earth by a single conductor. Numerous cases of side flashes from the rod into some part of the building have been recorded. The following recommendations based on minimum inductance and screening are made:

Assuming a pointed roof for simplicity of illustration, a rod should be carried up high enough to act as an electrode for the lightning arc probably six feet or more, basing the distance on photographs of the part of the rod rendered luminous by the lightning. From a point about midway up on this rod, at least eight copper or iron wires should be attached; a wire passes to each corner of the roof and one at each mid-point. Each wire is carried directly down to a salted pipe-earth. At the eaves a horizontal metallic connection should be made to equalize the potentials and again at the ground line. The natural inclination of high frequency currents to spread over a surface will tend to prevent a side stroke toward the interior of the building. The multiple earth will tend to equalize the potential over the entire building. With a given amount of copper, the more it is subdivided into multiple paths, the surer the protection.

The foregoing is intended to cover only the principle involved and will have to be altered somewhat to meet architectural demands.

## CEMENT AS A RESISTOR.

Some time ago the possibilities of trouble with lightning-arresters on a system using cement resistors between the neutral of the system and ground suggested the necessity of studying its characteristics. It may be noted in passing, that arresters for non-grounded neutral systems require an extra leg between the multiplex connection and earth to limit the dynamic potential across the arrester in case of an accidentally grounded phase. If the resistance in the neutral rises appreciably, the condition is equivalent to a non-grounded neutral system.

Another important phase of the subject is related to the use of cement in poles and as anchors or foundations for electrical transmission towers. In the event of a shattered insulator, the cement or concrete will be called upon to carry either the charging current or one phase according to the connections. In this case the question of conductivity is a minor matter and attention should be directed to the possibility of disintegrating the cement by overheating. A series of tests was carried out to determine the characteristics to apply to the foregoing problems. The writer is indebted to Mr. R. H. Marvin for the tests. The report is so replete with data and conclusions it is given verbatim.

These tests were undertaken to determine the suitability of portland cement as a material for resistances, especially its use with large currents and on high voltages.

They tend to show the following conclusions.

At moderate temperatures the resistance depends simply on the amount of moisture in the cement and becomes extremely high if the moisture is removed, either by long drying or artificial heating. The addition of sand increases the resistance, acting apparently as an insulator distributed through it. When cement is heated it at first increases enormously in resistance as the moisture is driven off, but at a red heat it again becomes as good a conductor as when cool and damp. With the same voltage per unit of length, a moderate voltage, as 600 volts, will not heat the material above 100° cent. so as to pass the interval of high resistance; but a higher voltage, as 8000 volts, can pass this interval and heat the resistance to incandescence.

The subject will be treated under the following heads:

1. Effect on resistance of cement of various proportions of sand.
2. Change in resistance with age.
3. Behavior of cement resistances on constant potential circuits.
4. Effect of moisture on resistance.
5. Conductivity at high temperatures, or pyro-conductivity.
6. Change, from conductivity due to moisture, to pyro-conductivity with high voltages.
7. The properties of cement as a resistance when used in the form of concrete.

Subjects 1 and 2 are naturally included in the same tests and will be treated together.

1 and 2. *Effect on resistance of cement of various proportions of sand, and change of resistance with age.* Resistances were made up in the form of rods of square section. These rods were 14 in. long and had a cross-section approximately 2 in. by 2 in. or 4 sq. in. At 1 in. from each end, sheet iron terminals were inserted while the cement was soft. These terminals consisted of a strip of 17 mil. soft sheet iron, 2 in. wide and 2.5 in. long with a projecting lug for attaching a wire. The strip was slit for 2 in. into eight strips 0.25 in. wide; each 0.25 in. strip was then twisted through a right angle, giving a fork like appearance. This terminal gave a large area of contact without mechanically weakening the block. The terminals were thus 0.25 in. long in the direction of the axis of the rod, but in obtaining the specific resistance their distance apart, center to center, or 12 in. was taken.

The materials used were:

Edison portland cement and ordinary building sand.

Five different mixtures were tried, six rods being made of each. The materials for each set of six rods were mixed together so as to insure uniformity. The proportions were as follows, in parts by weight.

Set *A*. Cement 1 Water 0.3
Set *B*. Cement 1. Sand 1. Water 0.45
Set *C*. Cement 1. Sand 2. Water 0.74

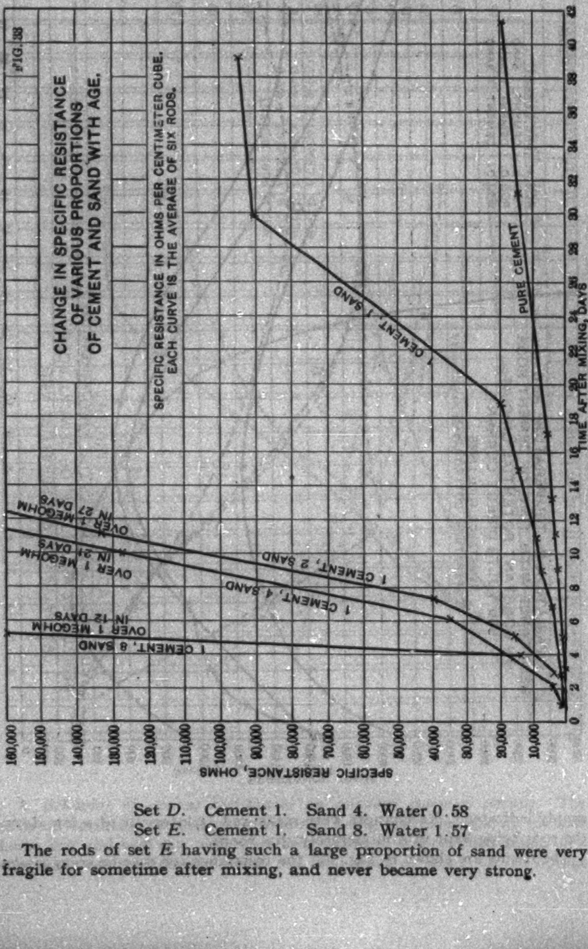

Fig. 33.—Time versus resistance of cement and sand

Set *D*. Cement 1. Sand 4. Water 0.58
Set *E*. Cement 1. Sand 8. Water 1.57

The rods of set *E* having such a large proportion of sand were very fragile for sometime after mixing, and never became very strong.

The resistance was measured on a storage battery circuit of about 110 volts by means of a voltmeter of known resistance. Resistances above a megohm could not be accurately measured, so when they occur they are

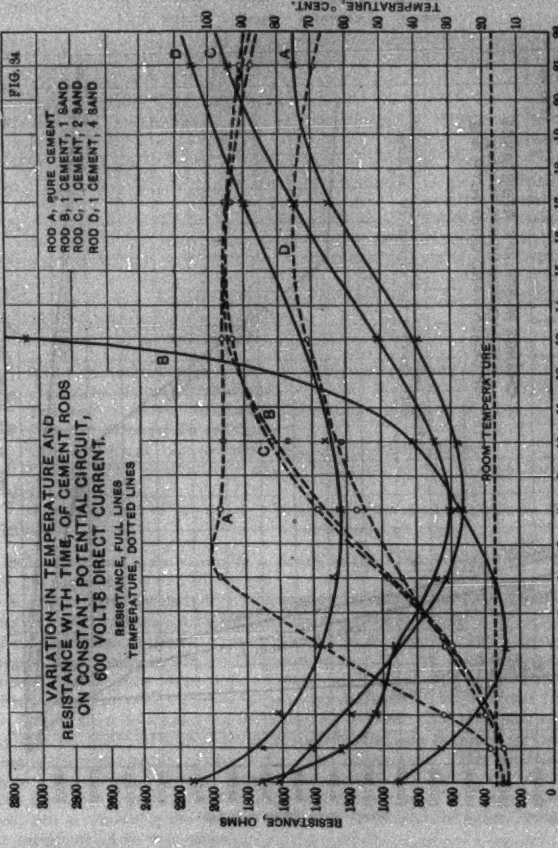

FIG. 34.—Application of power to cement resistors. These curves are of the early stages

simply indicated. Resistances were measured at intervals of a few days, the rods being kept in a moderately dry room.

The results are shown in Fig. 33, the resistance for ease in comparison being expressed as specific resistance, or resistance in ohms between opposite faces of a centimeter cube. These curves show a gradual increase in resistance with age; due apparently, mainly to drying out of moisture, but possibly in part to the chemical changes in setting. They also show a large increase in resistance with the addition of sand.

FIG. 35

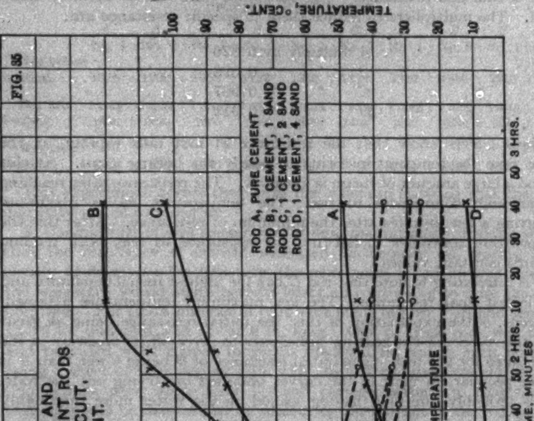

FIG. 35.—Application of power to cement resistors. These curves are the continuation of the previous curves to a smaller scale

3. *Behavior of cement resistances on constant potential circuits.* The tests on variation of resistance with age being concluded and all the rods being dry and well set, tests were next made to observe their action on a constant potential circuit. One rod from each of sets *A*, *B*, *C*, *D*, was

taken and soaked in water for sometime so as to insure uniform moisture conditions. After draining a few hours they were connected to a 600 volt direct-current circuit and readings taken of temperature and resistance at short intervals. The readings are plotted in the curves of Figs. 34 and 35. Fig. 35 is the continuance of Fig. 34 to a smaller scale of time and resistance. The resistances are those actually measured. The multipliers to reduce these to specific resistance are:

| | | |
|---|---|---|
| *A* | multiply by | 0.836 |
| *B* | " " | 0.898 |
| *C* | " " | 0.907 |
| *D* | " " | 0.912 |

These curves show that the resistance at first falls rapidly, at the same time the temperature rising to nearly the boiling point. At this period a large amount of steam is given off. The resistance after reaching a minimum commences to rise. The temperature has a maximum occurring a few minutes after the minimum of resistance. After this the temperature continues to fall and the resistance to rise, both tending towards constant values.

It is interesting to note that rod *D* has the highest initial resistance and the lowest final resistance. The low maximum temperature attained, 75° cent. is the explanation of this, the initial resistance being so great that the rod could not heat up sufficiently to drive off its moisture in the time taken for the test. The initial resistance of *B* being lower than *A* is rather peculiar, in view of the curves obtained on drying out the rods, but is probably due to *B* having soaked up the water more thoroughly than *A*.

The amount of energy dissipated before the resistance has increased to a prohibitive extent is also of interest. If we consider three times the initial resistance as the permissible amount, then these rods gave the following results approximately.

| | Time in minutes to reach three times initial resistance on 600-volt circuit | Kilowatt-hours absorbed and dissipated | Average kilowatts input |
|---|---|---|---|
| Rod *A*......... | 28 | 0.0885 | 0.190 |
| Rod *B*......... | 13 | 0.0713 | 0.329 |
| Rod *C*......... | 26 | 0.0845 | 0.195 |
| Rod *D*......... | 56 | 0.1170 | 0.125 |

4. *Effect of moisture on resistance*. The tests already described indicate the importance of the moisture in the rods, but to further prove this point the following test was made. Two rods of each set, *A* to *E*, were taken. They were soaked in water for several days. When removed they were allowed to drain a few hours, and the resistance was then measured. They were next slowly heated over a bunsen burner for several

hours so as to drive out the moisture. After cooling the resistance was measured. They were again soaked in water as before and the resistance measured. The specific resistance in each case is given in the following table. Resistances over one megohm could not be accurately measured, so are simply indicated.

SPECIFIC RESISTANCE

| | *A* | *A* | *B* | *B* | *C* | *C* | *D* | *D* | *E* | *E* |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. 1 | No. 2 | No. 1 | No. 2 | No. 1 | No. 2 | No. 1 | No. 2 | No. 1 | No. 2 |
| **Wet before heating......** | **1078** | **1200** | **1552** | **1137** | **1930** | **1764** | **2240** | **1800** | **2910** | **3270** |
| **Dry after heating......** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** | **1 meg plus** |
| **Wet after heating......** | **955** | **1270** | **1310** | **1483** | **2550** | **2810** | **2855** | **3490** | **6520** | **6420** |

This experiment agrees then with the others in showing that the conductivity is due to moisture.

5. *Conductivity at high temperature or pyro-conductivity.* Having shown that the resistance of cement increased enormously on heating sufficiently to drive out the moisture, the next point taken up was whether the resistance would again become lower on continuing to raise the temperature. For this a number of rods were made of pure Portland cement, 15/16 in. diameter and about 6 in. long. One of these rods was taken and provided with copper terminals placed 1 in. apart, each terminal being a sheet of strip copper ¾ in. wide, tightly clamped around the rod. Connections were made to a 116-volt storage battery so that the resistance could be determined by measuring the current in the rod and the voltage across it. The current was measured by a d'Arsonval galvanometer with adjustable shunt, and the voltage on a Weston voltmeter. Arrangements were made to heat the short length of rod between the terminals with a blast lamp. It was considered best to use as high a voltage as possible for measurement so as to render thermo electric effects negligible, preliminary tests having shown that these were very noticeable with low voltages. The following table gives a summary of the tests. The cement rods had been allowed two days to dry and set.

Variation of resistance of cement rod on heating.

| Resistance megohms | Approximate temperature |
|---|---|
| 0.144 | Cold before heating. |
| 54.500 | |
| 45.900 | Slowly heating up |
| 76.700 | |
| 8.970 | Beginning to get red hot. |
| 0.780 | Red hot. |
| 0.178 | Partly white hot. |
| 0.131 | White hot. |

These results are rather rough owing to the impossibility of heating the rod uniformly, and the absence of any means of obtaining the exact temperature, but they indicate the general principle that as the moisture is driven out the resistance increases enormously, but as red heat is approached, it falls rapidly, and at white heat is practically the same as when cold and moist. That this fall in resistance is due to temperature and not to a permanent chemical change is shown by the resistance returning to its high value when the rod cools.

The cement was rendered very weak and brittle by the heating, resembling a piece of chalk.

6. *Change from moisture conductivity to pyro-conductivity with high voltages.* The experiments of the previous section have shown that the conducting properties of cement depend upon three distinct states of the material. These are:

1. A condition of good conductivity depending in value upon the amount of moisture present. It is on this account liable to wide variation with time, and completely disappears when the temperature is raised to the boiling point of water.
2. A state of low conductivity, approaching that of a good insulator, when the cement is dry and its temperature below a red heat.
3. Another condition of good conductivity at and above a red heat; the resistance at this stage being nearly the same as in the first.

It was in accordance with these properties that in the test of section 3 the temperature of the resistance rods never rose above 100° cent., the period of high resistance being insurmountable by the moderate voltage employed.

To see if, with a higher voltage per unit length, the interval of practical insulation could be bridged, the following experiments were undertaken.

A number of pure portland cement rods were made $\frac{3}{4}$ in. in diameter and about 6 in. long. Copper bands which could be clamped around these at any point were used as terminals.

The first experiments were made on 600 volts direct current, the terminals being set at various distances apart down to 0.25 in. Even with this small distance between terminals it was impossible to pass the insulation stage. There would be a violent production of steam for a few seconds, and then no further action. Frequently the rods would crack in two from the high steam pressure produced.

Experiments were next tried using a 25,000-volt, 60-cycle, testing transformer. On account of the small capacity of the generator supplying this, the current available was very small; also the regulation was poor causing a large drop in voltage under load. Tests were made with the terminals on the rods 4 in. apart. The voltage was adjusted to about 8,000 volts at no load. If the rod was quite damp when put on the circuit, the rush of current was usually so great as to open the circuit breaker. When slightly dryer a large current would flow for a short time, lowering the voltage very greatly; at the same time incandescent spots and streaks would form on the rod from which spectacular streams of flame would shoot out a foot or more, continue for a few seconds and then disappear. The voltage would then rise to its no-load value indicating a very high resistance. The experiment could be repeated by soaking the rod in water for a few minutes. But finally a rod was found coming within the capacity of the apparatus. The voltage being thrown on the incandescent streak spread from one terminal to the other, the rod gradually heating up all over. It ran quietly for about a minute, the voltage falling to 2000, and could probably have been kept at incandescence indefinitely had the power been available, but the apparatus beginning to heat, the current had to be cut off. After the rod had cooled, the application of 8000 volts produced no effect, showing that moisture is necessary to start the action. Probably the rods could in all cases have been heated to incandescence had the power been available.

These experiments at 600 and at 8000 volts show that the passing of the period of high resistance is not so much a question of average potential gradient, as of maximum potential available. It is reasonable to suppose that the material becomes conducting in spots, and that the high voltage will concentrate on any high resistance portions.

It is also important to notice that to start the action the initial moisture conductivity is essential.

7. *The properties of cement as a resistance when used in the form of concrete.* As in most cases when portland cement has been used for a resistance in practice it has been mixed with broken stone and sand to make concrete, some further tests were made with this material. The proportions by weight of the material were about as follows:

| | |
|---|---|
| Edison portland cement | 100 |
| Sand | 200 |
| Broken limestone from ¾ in. down to powder | 100 |
| Broken limestone, 2 in | 100 |
| Water | 65 |

This mixture was molded in wooden boxes to form blocks 10 in. by 9. in. by 7.75 in.

*Variation of resistance with age.* For this a column of six blocks was built up. The blocks were joined together with pure cement mortar, only enough being used to fill up the irregularities. Several strips of sheet iron were placed at the top and bottom for terminals, being bedded in cement mortar. The dimensions of the finished column were 48½ in. between terminals, and 10 in. by 9 in. in cross-section. The blocks being made at different times were from two to three weeks old, and having stood out doors and been soaked with water in setting up the column their condition was rather indefinite. The following table shows the resistance for the first six days after building the column.

| Time after buildings, days | Resistance ohms | Specific resistance |
|---|---|---|
| 0 | 920 | 4340 |
| 1 | 898 | 4230 |
| 3 | 1068 | 5030 |
| 5 | 1178 | 3560 |
| 6 | 1177 | 5555 |

As would be expected in such a large mass of concrete the change in resistance is very slow.

Behavior of concrete blocks on constant potential circuits. The circuit used for this test was a 2300-volt, 60-cycle lighting circuit. A single block was used, being set up so as to give a length of circuit of 7.75 in. and a cross-section of 10 in. by 9 in.; the terminals as before being strips of sheet iron.

The action in this case was exactly the same as in the test made with the small rods. The current was at first large but fell rapidly as the moisture boiled off, the rod becoming almost an insulator in a short time, Pouring water over it and allowing it to soak in would bring the resistance back more or less to its original value. The action took place so rapidly that it was very difficult to obtain good tests. The following figures will, however, give some idea.

In the first test made, the current started at about 15 amperes and fell in 23 minutes to .2 ampere.

In another test made some months later and when the block was quite dry, the current started at 2 amperes, reached a maximum of 4.4 amperes in 1 minute and fell to one ampere in 3½ minutes.

*Summary and conclusions.* The tests made with cement rods having different proportions of sand show a progressive increase in resistance with increase in the amount of sand, leading to the conclusion that the sand acts practically as an insulator distributed through the cement, so diminishing the effective cross-section of the rod.

All the experiments on the change in resistance with age or with heating indicate that at moderate temperatures the conductivity depends almost entirely on the amount of contained moisture. It would appear probable that the moisture dissolves a portion of the cement to form an electrolyte which being diffused through the body of the cement conducts the current, the solid part of the cement simply acting as a container for this electrolyte.

The studies of concrete while not as complete appear to agree with these conclusions.

The experiments on resistance at high temperatures and at high voltages show that cement possesses in addition to its low temperature or moisture conductivity a high temperature or pyro-conductivity. Also that a high voltage is able, in some manner to bridge the interval of high resistance and raise the material to incandescence.

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# TESTS WITH ARCING GROUNDS AND CONNECTIONS

BY ERNST J. BERG

It has long been known that when an arcing ground occurs in a system, abnormal voltages and consequent failure of apparatus often result. This series of tests was started with the hope of being able to deduce some mathematical expression which would represent these phenomena with reasonable accuracy. The mathematical expression did not materialize, but in view of the importance of the subject, and believing that the results will prove of some interest and value, I give them in the following paper. The theoretical explanation might form the subject of a future paper.

In the tests power was supplied from a three-phase turbo-generator operated at 25 cycles and 11,000 volts. During the tests this generator also furnished power for railway and other purposes, so that the load, and therefore the wave-shape, was not the same throughout. Some endeavor was, however, made to find whether the outside load affected the readings, but the results were not conclusive and rather negative. It seemed, therefore, that at least in a general way the impressed, or rather the generated wave-shape of electromotive force was of little importance.

The current was carried to the experimental station through a three-conductor cable 4000 ft. long. The diameter of each conductor was 0.365 in. and the resistance 0.31 ohms. The capacity between conductors was 0.27 mf. and between each conductor and the other two and ground 0.45 mf. Two sets of 110-kw., single-phase, core-type transformers of similar type were used; one to reduce the voltage from 11,000 to 370, the other to raise the voltage from 370 to 33,000, the voltage used in the experiments. The arcing grounds were established on the high potential side of the transformers.

Fig. 1 gives the principal dimensions of the step-up transformers; that is, the transformers at the terminals of which the experiments were made.

The low-potential winding was made in four coils, each of 24 turns. These coils were placed nearest the core. The connections of the coils are shown in Fig. 2. The inside coil on one leg was connected to the outside coil on the other, and all coils were connected in series for 370 volts. The high-potential winding was in 18 coils, nine of which were on each core. . The two outside coils, *A*, Fig. 3, had a tap brought out from the middle of the winding, the other coils, *B*, had no taps. The two *A* coils had each 426 turns, the *B* coils 482, making 8552 turns in all. The coils were connected as shown in Fig. 3.

In the paper one-half of the *A* coils is referred to as "the end coil," which, therefore, have 213 turns, or one-half of the turns of the *A* coils. The normal voltage between them is 2.49% of the primary voltage.

Terminals were brought out from the taps indicated. The exciting current was 3% of the full-load current, the core loss 1.2%. Primary and secondary resistances were each 1% The total reactance was 3.5%. The capacity between the primary and secondary winding was 0.003 mf., and the capacity between primary and secondary and ground was approximately the same. In all experiments the transformer cases were grounded.

The arcing connections between terminals or to ground were made by approaching a small wire to the terminal. Unless stated to the contrary, the arcing connection may be assumed to have practically no resistance. As will be seen in one of the experiments, substantially the same results were obtained when a resistance of several thousand ohms was inserted in the ground circuit.

The striking distances were taken by means of needle gaps in series with which were resistances of such a value as to limit the current to about 0.5 amperes. It was found that this resistance could be varied over a wide range without affecting the results, but that the actual contacts in the spark-gap circuit must be carefully made, since if an arc was established in any of the connections local oscillations were set up and too high striking distances resulted. The striking distances given represent the highest values obtained after a whole series of tests. These high values were, however, quite consistent so that tests repeated different days would check within a few per cent.

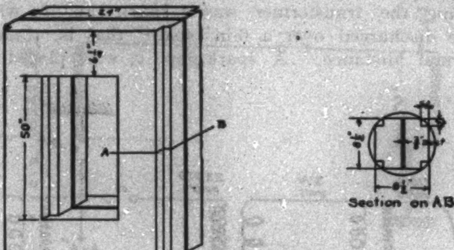


Figure No.1

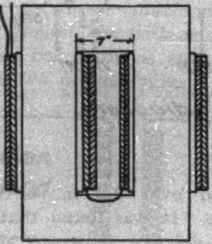


Figure No.2.

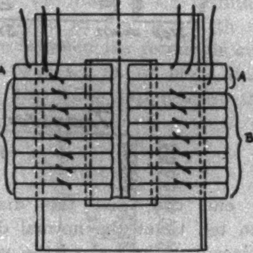


Figure No.3

The normal striking distance between lines at 33,000 volts was 2 in. The striking distance across the first two taps—820 volts—was so low as to make the reading uncertain—it was less than 0.03 in.

In the first test which is shown diagrammatically in Fig. 4 one of the high-potential terminals of a 33,000-volt transformer was connected to one of the high-potential lines of another similar idle transformer through an arc. To introduce considerable capacity in the system, the other high potential line was grounded as was also the transformer iron. As the terminals *a* were brought within striking distance, a series of static sparks was established, which by their bluish-white color and snappy sound indicated a very high frequency.

Shunting the transformer was a spark gap, *b*, which at the time discharged over a 6-in. space; that is, three times the normal distance. A spark-gap, *c*, was placed across the end coil, and this discharged over 0.3 in., or more than ten times the normal distance. It was found that gap *d* placed at the end of the winding did not show any abnormal voltage.

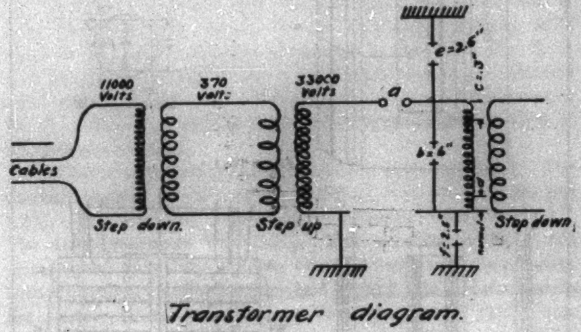


FIG. 4

Needle gaps were also placed at *e* and *f*, between the end of the winding and ground, and these discharged over a distance of 2.5 in., showing that the winding was subjected to excessive voltage not only between turns, but also to ground.

In the second test, Fig. 5, the same general arrangement was used, but the ground connection of one of the lines of the step-up transformer was removed. Under this condition the spark at *a* was very faint, due to the slight charging current, and the voltages were very much reduced as seen in the figure, in which for convenience sake the striking distances are inserted directly instead of the spark gaps. These two experiments indicate what might take place when transformers are connected or disconnected by an air switch, or a switch which permits of some oscillations before the circuit is definitely made or opened.

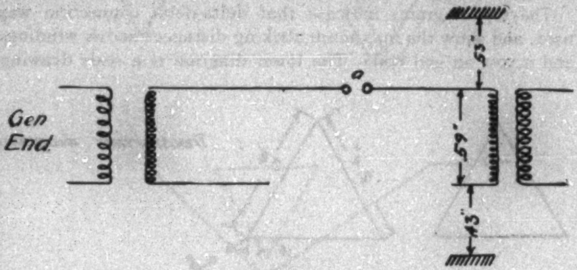


Fig. 5

In the third test an arcing ground was made at the terminal of the step-down transformer as shown in Fig. 6. With an arcing ground, the striking distance between the terminals and between one terminal and ground was 4.1 in. or more than double the normal value. Across the 2.5% tap nearest the arcing ground the striking distance was more than 15 times the normal, but no apparent abnormal voltage existed at the end coils on the ungrounded side of the transformers.

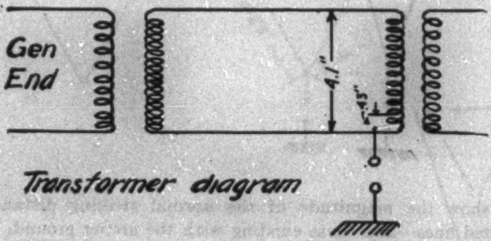


Fig. 6

The fourth test was made with transformers connected three-phase. Three transformers with the primaries and secondaries connected delta were used to reduce the voltage from 11,000 to 370; three others, with the same connection, to raise the voltage from 370 to 33,000 volts. One of the high potential lines, or rather the junction of two transformer windings, since no transmission line existed, was grounded by an arc, as shown in Fig. 7.

The top diagrams indicate that delta-delta connection was used, and show the maximum striking distances across windings and across an end coil. The lower diagram is a scale drawing to show the magnitude of the normal striking distance—in dotted lines—and those existing with the arcing ground.

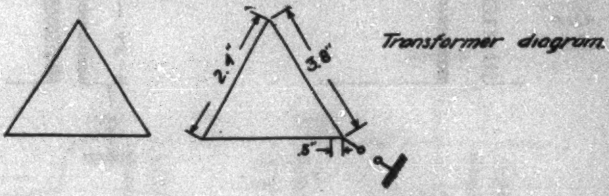
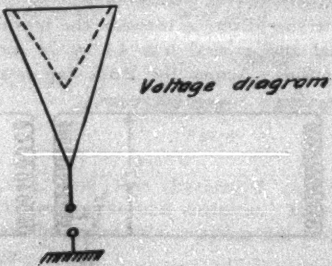


Fig. 7



It is interesting to note that the striking distance across the two transformers nearest the ground was 1.9 times the normal. The transformer opposite to ground was subjected to 1.2 times the normal voltage.

In the next two tests the step-down, as well as the step-up transformers, were connected open delta, or V. By referring to Figs. 8 and 9 it is seen that with this connection, particularly

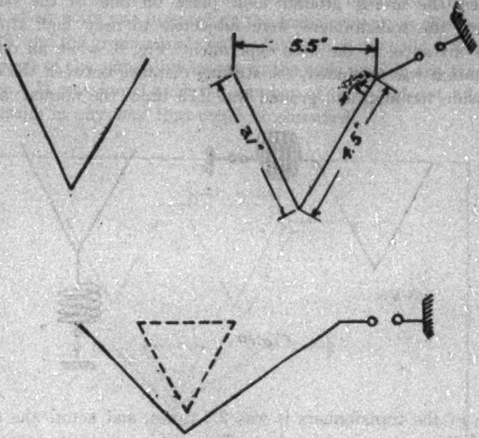


FIG. 8

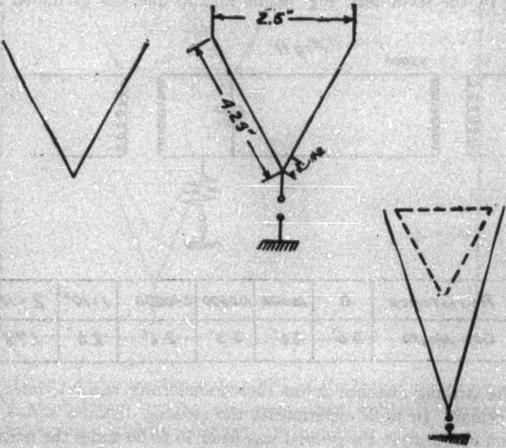


FIG. 9

when the arcing ground took place on one of the outside lines, the transformers were subjected to very high stresses. For instance, in the fifth experiment. Fig. 8, when an outside terminal was grounded, the striking distance between the other outside terminal and ground was 2.75 times the normal; across one of the transformers it was 2.2 times, and across the other 1.55 times the normal value. The striking distance across the first 2.5% tap was 0.45 in., or about 15 times the normal, across the next tap 0.3 in., or ten times the normal.

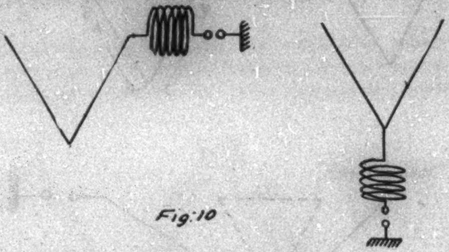
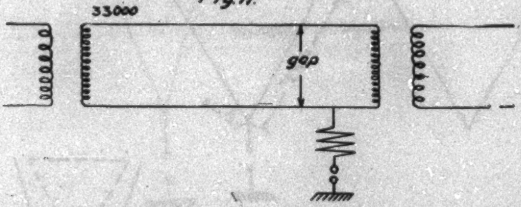


Fig: 10

In the sixth test, Fig. 9, the middle line was grounded and the striking distance across each transformer was 2.1 times the normal. In both experiments the striking distance across the end coil nearest the ground was from 15 to 20 times the normal, but no abnormal voltage was detected at the end turns opposite the grounded side.

Fig. 11.



| Resistance | 0 | 16000 | 160000 | 340000 | $1 \times 10^6$ | $2 \times 10^6$ |
|---|---|---|---|---|---|---|
| Gap length | 3.6" | 3.6" | 3.5" | 2.6" | 2.5" | 1.75" |

In the seventh test a very wide range of inductance in the shape of air coils was inserted at the transformers, as shown in Fig. 10, and the ground made on the line side of the coils. These coils were of the same dimensions as the coils used in the transformer. It was found that the number of turns did not affect the results in any way that could be classified.

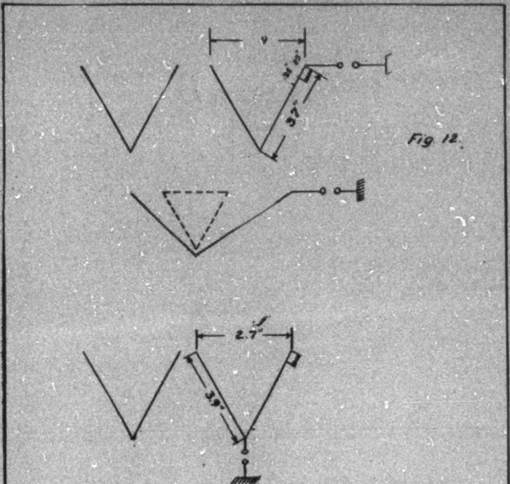


Fig. 12.

At times a large reactance, say 20% of the transformer turns, would show lower striking distances, then suddenly perhaps the wave-shape slightly changed, or something else happened outside of the experiments, and the striking distances would be even greater than when no coils were used. The coils seemed to resonate with some of the higher harmonics; and since there is probably a large number of higher harmonics, each coil found one which suited the natural frequency of the transformer winding and the coil.

The eighth test recorded in Fig. 11, shows the effect of resistance in the circuit of the arcing ground. The diagram and the table explain themselves, and show in a general way that arcing grounds over insulators, through wood, etc., are practically as destructive as grounds without resistance.

Electrolytic cells in series with resistance

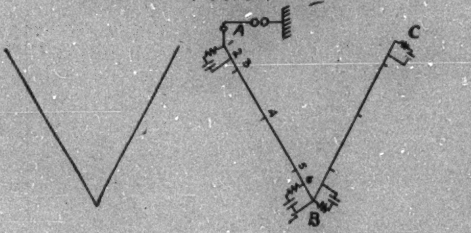


Fig. 13

Each cell consists of:-

175 Ohms.

| Volts | AB | BC | AC | 1-2 | 2-3 | 1-4 | 4-7 |
|---|---|---|---|---|---|---|---|
| Gap | 4 7/16 | 2 13/16 | 5 3/16 | .045 | .162 | 1 3/16 | 1 5/16 |

Various methods of relieving these strains, particularly the strains on the end turns, were tried.

For instance, in Fig. 12, which illustrates the open delta connection, the end coil was shunted by a resistance in series with a gap, the gap being so proportioned that a discharge would take place at abnormal voltage only. Various resistances were tried, but even the most favorable did not reduce the voltage entirely. By comparing Fig. 8 with Fig. 12, it is seen that the reduction in voltage across the first end turns was 50%, but the stress across the next coil was somewhat increased.

The voltages across the entire transformers were also decreased. It may be of interest to add here that this method of protection was quite effective at low voltages. This leads the writer to

Electrolytic cells in series with resistance

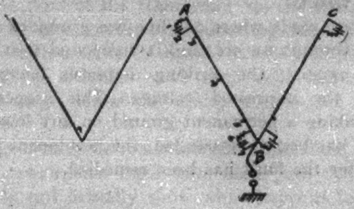


Fig. 14.

Arcing B

(Each cell consists of

1000 Ohms.

| Volts | AB | BC | AC | 6-7 | 5-6 | 4-7 | 1-4 |
|---|---|---|---|---|---|---|---|
| Gap | 3/4 | 3 5/16 | 2 13/32 | .135 | .258 | 1 1/4 | 1 5/16 |

500 Ohms

| (Volts | AB | BC | AC | 6-7 | 5-6 | 4-7 | 1-4 |
|---|---|---|---|---|---|---|---|
| Gap | 2 11/16 | 3 1/2 | 2 5/16 | .170 | .305 | 1 5/16 | 1 1/16 |

175 Ohms.

| Volts | AB | BC | AC | 6-7 | 5-6 | 4-7 | 1-4 |
|---|---|---|---|---|---|---|---|
| Gap | 2 15/16 | 3 9/16 | 2 3/8 | .151 | .365 | 1 3/8 | 1 3/16 |

believe that with very high voltages when local oscillations of considerable energy are set up in the shunted circuit, this method will prove of relatively little value.

Ordinary tin foil, mica and electrolytic condensers shunting the end turns were very effective in relieving the strain in the shunted coil, but transferred it to the next section.

Resistances in series with a few cells of electrolytic condensers caused some improvement as is seen by comparing Figs. 13 and 14 with Fig. 8.

Loading the transformers experimented with did not materially affect the results.

Finally, tests were made where one line was grounded permanently instead of through an arc, and it was found that no abnormal voltages existed, the striking distances being those corresponding to the impressed voltage. This suggests the advisability of making a permanent ground on any line which by some accident has become grounded, the permanent ground to be removed after the fault has been remedied.

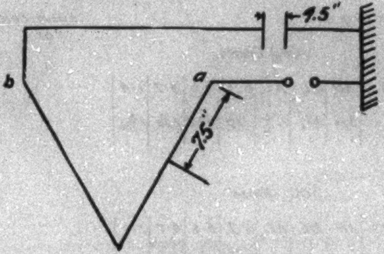


FIG. 15

Before closing it may be of interest to add an instance of the effect of an arcing short circuit which took place during one of the open-delta tests with the connections shown in the wiring diagram, Fig. 15.

Line *a* was grounded through an arc, line *b* connected to ground by an electrostatic voltmeter, having 4.5 in. distance between plates. As line *a* was grounded, an arc struck between the plates of the electrostatic voltmeter, resulting in a short-circuit on the transformers. At that time an arc struck from the terminal of line *a* to the terminal which was brought out from the middle of the winding, a distance of 7.5 in., or practically seven and a half times the normal striking distance. It is of course possible that the spark might have been still longer if the terminals had been further apart.

In conclusion it would seem as if with increasing line voltages it may be desirable to resort to some new methods of protecting the winding of transformers and other apparatus connected to the high-potential lines. One method might consist of a series of small electrolytic cells shunting the individual coils; by this arrangement these high-frequency surges would be transferred from each part of the tranformer to the lines. It seems unlikely that electrolytic cells shunting the lines but not connected to individual coils would entirely eliminate these internal disturbances, although with such cells there is no likelihood of the voltage across the entire transformer being materially increased.

Finally, it must be remembered that in these tests no high-potential transmission lines were used, and that, therefore, the results do not actually show what happens in a large system. From a few observations made in such systems the writer feels, however, that in general similar stresses result. Actual careful tests on such systems would prove of great value, bearing as they do on the choice of transformer connections.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 30, 1908.*

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# CRITICAL STUDY OF LIGHTNING RECORDS ON TAYLOR'S FALLS TRANSMISSION LINE

## (PAPERS BY J. F. VAUGHAN AND N. J. NEALL*)

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BY PERCY H. THOMAS

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The following study of the Taylor's Falls line lightning data has been made for the purpose of discovering what inferences as to the nature of the attack of lightning on a transmission line can be safely and properly drawn from the unusually complete data recorded.

*Interpretation of tell-tale papers.* The correctness of all inferences presumably depends on a correct interpretation of the significance of the various types of punctures in the tell-tale papers; hence this matter was given special consideration. A careful study of the original papers shows the punctures in the tell-tale papers taken from the gaps in the ground connection of the insulator pins to be of three sorts.

1. Very fine, almost invisible punctures, usually occurring in large numbers and scattered round a central point or points. These are often so numerous that the paper is actually eaten away for a small space, giving a superficial appearance of the second type. This first type is characterized by a sharp edge, looking almost as though it had been scorched and usually by a few small punctures in its neighborhood.

2. Distinct individual holes, varying in size from that made by a small needle to large holes, all having the appearance of having been torn in the paper. These all have rough hairy edges but show no signs of burning.

3. Individual holes of the general character of the last but with burned or charred edges. This type may show any amount

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*Presented at New York, May 19, 1908.

of burning from a slight scarring to the complete destruction of the paper.

In general these three types are clear and easily distinguished. They are clearly to be interpreted as follows:

*First type.* Puncture due to charging current taken by the pin in view of its static capacity to the line wire. This charging current evidently will exist under normal voltage conditions, if the width of the gap in the ground connection where the telltale is placed is sufficiently small to be broken down by the voltage normally existing. Trouble was experienced at first from the honeycombing of tell-tale papers during normal operation, since the ground gaps were set too small. The readjustment of these gaps is noticed in the large chart, Fig. 11, under date of June 10. When these gaps were finally set above the breaking limit of the normal voltage, punctures of the first type must have indicated abnormal voltages, and the size of the puncture indicated the amount of charging current taken by the pin or sometimes the number of times such voltages were repeated.

The *second type* above, indicated " spill-overs "; that is, the jumping of a static charge over the surface of the insulator. This was a very common occurrence in these experiments. Spill-overs are distinguished from the first type of puncture by their size. Only the finest punctures can be caused by the charging current to the pin itself, on account of its small static capacity. On the other hand, when the spark jumps from the line to the pin the static capacity of the line comes into play and also any charge coming to the line from the atmosphere and a much larger discharge results.

The *third type* is of the nature of the second, except that after the spill-over, current from the generator has followed.

The following analyses are based on the above interpretation of these paper punctures, which the writer has no doubt are substantially correct.

*Analysis of storms. Storm of July* 4. This storm is of special interest, since there happened to be no power on the line at the time the storm occurred. The direction of the storm is west to east, crossing the line two miles from Hugo at about pole 918. There are a number of relatively small punctured papers between the main centre of disturbance near pole 918 and the substation; those occurring beyond pole 1135, five miles from pole 918, appear to have been caused by the *first type* of sparking; that is, by charging current to the pin itself without discharge over the insulator. These punctures were made presumably before the taking off of the power from the line on the morning of July 4, or perhaps after it was put back before the papers were taken out on July 6. They may, however, have been made by waves of static from the disturbances occurring near the middle of the line. The first explanation, if true, means that these particular gaps were set so close as to show these fine punctures when there was no noticeable abnormal disturbance.

There seem to have been two distinct local disturbances in the neighborhood of pole 918. A heavy discharge must have struck at pole 918 on all wires and have traveled in both directions on all wires. The spill-overs tributory to this discharge on phase A appeared last at pole 928 in the direction of the sub-station, and at pole 906 in the other direction. On phase B spill-overs appeared last at pole 924 in the sub-station direction and at pole 909 in the other; on phase C there were small spill-overs to 909 (possibly to 894) and a large one at 924.

There must have been a second discharge near by, according to this analysis, centering at poles 931, 934, and 937. The spill-overs from this disturbance seem to have been confined to poles not distant from the center at pole 934 more than six or eight poles. And although three insulators were shattered near pole 934 there were apparently not more than four other spill-overs. It is possible that the very small spill-overs at poles 955, 958, and 961 were due to this same discharge. Their appearance indicates rather quiet static.

It so happened that this discharge, or these discharges, came on the section of line, a little over a half-mile long, between ground wire A and ground wire B. That this is the case seems certain, for the punctures of the papers are nowhere so large in the general region of that storm as around 918 and 934. It is unfortunate that the storm did not actually strike over one of the sections protected by grounded wire, as this would have given more valuable evidence as to the protective effect of such wires than now exists.

As a matter of fact nearly all of the tell-tale papers in the *ground connections* of the overhead ground wire B discharged enough electricity to show a hole perhaps one-half as large as the largest punctures in the tell-tale papers in the insulator pin-ground wires on the unprotected portion of the lines. These overhead ground punctures, further, grew smaller in size from the end nearest the maximum disturbance to the other end. They are quite as likely to have been caused by the static wave passing down the transmission line from the region of pole 918 as by the direct effect of the disturbance on the overhead ground wires. They may, of course, conceivably be due to a suddenly released bound charge, but they seem to be much too large for this. The evidence against the "bound charge" hypothesis is summarized in the second paragraph below. Two insulators were shattered under this overhead protection, one only one pole within, the other four poles within. This shattering probably had little to do with the effectiveness or lack of effectiveness of the ground wires, since the disturbance arose on an unprotected portion. The grounded wires on the other side of the unprotected portion of the line showed very much smaller punctures in their ground connections and only three in all located next to the end of the section.

The smaller of the two main disturbances, near pole 934, which was the one nearer the last described section of ground wire (type A) was central about seven poles away, while the greater disturbance near pole 918 was central about five poles from ground wire B section. No very satisfactory conclusions can be here drawn as to the protective power of the overhead ground wires, since the storm did not strike so as to give them a trial. It may, however, be safely concluded from the tell-tale papers that the ground wires are very active and pass much current. This is almost certain to be helpful. The other types of overhead ground wires located at distances from one to six miles, seem to have taken no discharge of any particular significance.

It is very important to note the nature of the discharges in the tell-tale papers of the lightning rods that are entirely separate from the line structure. In the case of nearly every lightning rod on the whole system small punctures were observed, usually much less than the size of a normal spill-over puncture on the line, but very numerous. In one case, not near the centre of disturbance by two miles, pole 820, what would be taken as a very severe spill-over puncture if found in the insulator tell-tales, was observed. This must have meant a severe direct stroke. In none of these cases of spill-over size discharges in the lightning rods was there any sign of disturbance on the adjacent portion of the line. From these observations on lightning rods it may be concluded that the disturbances on the line are in all probability due, at least in their severe form, to direct charges from the air and not to the accumulation and release of bound charges on the line. The latter could not occur on the rods; and if the rod discharges come directly from the air, it is evident that the line charges as well do so in the main, since both sorts seem of the same nature and of the same general magnitude. Furthermore, the heavy discharge at the lightning rod near pole 820 should have produced a severe discharge on the line, if the sudden release theory be the right one, for the conditions must have been particularly favorable at this time.

During this very active storm there were only very few discharge indications on the station arresters. At the power-house there were very small discharges on all three legs of the horn arrester. At the sub-station there were discharges, both series and shunt, in leg C on the low equivalent and a discharge in leg A on the electrolytic. This is very significant, for the storm was severe and prolonged in the center of the line and yet was hardly noticeable at the station arresters; in other words, the disturbances did not travel to the station without a considerable loss of energy.

*Storm of August* 18. This storm followed the direction of the line from sub-station toward power-house pretty closely and caused apparently five principle disturbances. The storm first made itself felt at or about pole 1387, where it caused spill-overs on all three line wires in the immediate neighborhood, especially on A and B. Here it very possibly started a short-circuit on the system through wire B on pole 1387 and probably through either leg A of the low equivalent or the horn arrester at the power house or leg A of the electrolytic arrester at the sub-station. This, then, may be taken as the cause of the dip in voltage referred to in the notes of this storm. Then nearly a mile farther on another discharge of great severity occurred at or about pole 1357. This destroyed several insulators and probably caused another short-circuit through wire C on pole 1341 and through leg A on one of the above arresters or perhaps more than one. This shut down the power house as reported and for the rest of the storm there was no power on the line. There are no more evidences of burning of papers.

Poles 1342 to 1385 had the ground connections removed from the pins and can show the actual discharges only by the shattered insulators and the split poles. Heavy spill-overs occurred on wires A and C on the pole having grounded pins nearest to the disturbance at pole 1351 and spill-overs were continued for nine poles on wire A. Spill-overs on other wires seemed to stop at pole 1341. Two or three spill-overs occurred in the next third of a mile on wire C, the last one on pole 1314, being one of the most severe of the storm. This spill-over was probably due to a separate disturbance.

No more very serious spill-overs occurred, though there was a single one of some violence at pole 909 wire A, four poles under the overhead ground wires, type B. This is significant, since there is no discharge of any importance at all in the neighborhood outside of the ground wire section. A single very severe spill-over occurred at pole 563 on phase C. No other spill-over occurred near it.

Overhead ground wires B were active, since at nearly every grounded pole a hole occurs in the overhead ground tell-tale papers of the size of a large spill-over puncture. There does not seem to have been any other evidences of a discharge in this neighborhood except that at each end of the ground wire section a line spill-over occurs on one wire, though these are different wires, and both are within the overhead grounded wire section. This looks suspicious, as the line spill-overs either cease on the line wires or at least become very much smaller exactly at the ends of and outside of the ground wire sections. There is apparently no evidence to show what is the phenomenon causing this particular condition.

The series coil tell-tale papers in this storm are very significant. The choke-coils at pole 1356, within one pole of shattered insulators on both sides on one wire and very close on all wires, had all three papers burned up, showing a very violent discharge in shunt to the coils, enough to ignite the papers. The papers for the coils on wires A and B at pole 1230 were burned up, this pole being a distance of two and a half to three miles from the nearest disturbance. There is a small puncture in the series coil in wire A at pole 1615, five miles in the other direction from the nearest discharge of any apparent severity. As these coils have only twenty turns of conductor of one foot diameter, probably not equal in inductance to more than a hundred yards of line wire, a very sharp wave-front is shown by these series coil discharges.

The above storms have been taken as samples. The analyses of the others have been made similarly, but the results can be best studied by topics.

*Protective power of overhead ground wires.* In making inferences on this subject, the most important one of all in some ways, it is necessary to use the greatest caution not to be misled. The data are not as full as was to be hoped but are nevertheless better than any definite data obtainable elsewhere.

*Ground wire A.* This section was subject to some disturbance, more or less, in five storms. There was one spill-over on an insulator in this protected section due undoubtedly to a disturbance outside the section, and four punctures in tell-tales of equivalent size in the grounds from the overhead wires, all in the storm of July 4. In only one instance was there any violent disturbance in the immediate neighborhood of these ground wires, viz., July 4. This occurred just outside the protected section. The overhead wires did not seem to have much effect. This was not of the most approved form and not much was to be expected of it.

*Ground wire B.* In case of this section there were fifteen spill-overs of all sizes over insulators under the ground wires and twelve more or less equivalent punctures in the ground connection of the overhead wires. There were six storms in which records are furnished, but only two in which punctures of spill-over magnitude occurred. In one case the centre of discharge was just outside of the grounded section and in the other was directly over it and did not extend outside. In the former case two insulators were shattered, one located one pole inside the protected section, the other four poles inside. This probably had little to do with the effectiveness or lack of effectiveness of the overhead ground wire. In the latter case, where the line showed spill-overs and the attack was in the grounded portion, the discharges seemed to occur near the two ends mainly as though there had been two independent discharges. The protective power does not seem to have been particularly effective here.

*Overhead ground C.* Records on this section are given for six storms, none however showing any discharges of any serious amount near this section. In only one case was there a noticeable discharge in any ground connection from the overhead ground wire. There was, however, no spill-over on the line wires on this section. This type of overhead ground is not a good one and in no case seems to have exercised much if any protecting power, nor to have had an opportunity to exercise any.

*Ground wire D.* This section is reported in six storms, two line spill-overs are shown on same pole, and nine more or less prominent discharges in the ground connection of the overhead wires, none being larger than 0.1 in. and most being smaller. No severe storms appeared to have attacked this section of the line. However, the two spill-overs were fairly severe and occurred six poles from the end of the section. The middle pole is eleven miles from the ends.

While the overhead ground sections as shown in the records are very active in discharging current, it is doubtful whether any of them would be wholly effective, as installed, in protecting the line wires from every severe discharge, such as occurred a number of times on this plant. It seems probable that the line wires would share the most severe discharges that attack the ground wires; the danger is that the latter are neither well enough spaced from the line wires nor often enough grounded completely to protect the line wires.

*Lightning rods*. There were six spill-overs on the line on the section protected by type A lightning rods on pole tops in five storms, and four more or less severe punctures in lightning rod papers. In the storm of August 4 and 6 there was one severe discharge in which there were three insulators shattered on this section and some very severe spill-overs but the lightning rod papers seem to have been omitted or destroyed, except a few at the end away from the disturbance. A very severe discharge occurred at pole 1028 three poles from the lightning rods, but no noticeable discharge occurred in the ground connections. The line, however, was evidently not protected. Although the rods will undoubtedly take such discharges as come to them, they probably cannot be relied upon to protect the line wires and insulators. They will undoubtedly, except in very extreme cases, however, protect the poles from injury.

*Lightning rods B*. These rods showed minor activity in all or nearly all storms, and greater activity in the three August storms which were centered within five miles or less of this section. This activity consisted in a multiplicity of very fine punctures aggregating a good size hole in the case of some ten or twelve rods. In addition on July 4, there was a violent discharge showing what would be considered one of the most violent spill-overs in an insulator pin ground. The center of the July storm was over two miles away, but some smaller disturbances evidently occurred nearer to this special arrester discharge.

*Lightning rods C and D.* These showed very much the same phenomena as the other types: activity with small punctures, many per paper—in about one-fourth of the rods—nothing on many of the intermediate poles. The active poles were pretty evenly distributed. There were no disruptive punctures of magnitude in the lightning-rod grounds. There were, however, no disturbances in the immediate neighborhood of these rods.

*Line choke-coils.* Choke-coils were located at poles 986, 1203, 1356, 1615. The storm of August 18 was severe at pole 1356 and moderately severe at poles 800 to 900. The tell-tale papers at pole 1356 were all burned up, these at pole 1203 three miles away were burned up in wires A and B, and a fair-size explosive puncture occurred at pole 1615, five miles away. Three good size punctures occurred also in the coils at pole 986 in wires B and C about two miles from the nearest disturbances.

This appears to show that charges of some magnitude pass along the line or possibly that their effect is increased by oscillation. It must be remembered that a ground on the line, lasting for even a very small fraction of a second, will cause the full static charge of the line on the one side of the choke-coil to pass by to earth, not merely a charge received from the air. Also that a burned paper is quite likely to be merely ignited by a spark of some violence, when it may be subsequently consumed by natural causes. This action is known to have actually occurred.

## EFFECTIVENESS OF ARRESTERS.

*Storm of June* 25, *not severe.* A relatively small but sharp discharge occurred at pole 1571, four and a half miles from the sub-station. Small static discharges occurred on one leg in the sub-station low-equivalent arresters in both series and shunt gaps and on one leg in the series gaps only. On the electrolytic at the sub-station, discharges occurred in all three legs, and two showed the following of a small quantity of generator current. The discharge on the line caused spill-overs on all three wires at the same pole. The low equivalents at the power house did not discharge.

*Storm of June* 29, *not severe.* This storm showed no spill-overs except the shattering of two insulators at poles 1474 and 1478 causing a short-circuit. There was no evidence of a discharge on the low-equivalent arresters at the sub-station, seven miles away, nor on the electrolytics at the same place.

The plant was shut down by this experience. There were no arrester discharges at the power house.

*Storm of June* 30, *not severe*. In this storm which attacked the line four miles out from the power house, all legs of the power-house low-equivalent arresters discharged, showing signs of dynamic current in the series gaps, but only a good static puncture in the shunts. The power-house horn arresters discharged only in leg B, but showed a heavy burning in the tell-tale paper of the resistance shunt ground connection, and a smaller burning of the paper in the main ground. These discharges of this storm out on the line were relatively severe and eight insulators were shattered, distributed on all three wires. No injury was done to station apparatus. On legs A and C the only arrester to discharge was the low equivalent. Furthermore, on line wire C there were two heavy spill-overs only a mile from the station, and two more spill-overs a little farther off. The sub-station arresters showed no signs of discharge. In all probability there was no discharge on the line within some 35 miles of the sub-station.

*Storm of July* 4, *severe, no power on line*. Although this storm, which has been already analyzed, was very severe, no great disturbance was manifested at the stations. The disturbance was centered at the middle of the line about 20 miles from each end. At the power-house the horn arrester discharged in all phases and the low equivalent probably in leg C, series and shunt, and the electrolytics at the sub-station in leg A. The discharges in the horns were small while those in the others were relatively large. The low equivalents at the sub-station discharged faintly in leg C. This is an interesting case, showing that the very severe discharges do not necessarily carry with power for half the length of the line. The nearest real spill-over to the sub-station seems to have been at pole 1135, 14 or 15 miles away though a number of quiet static punctures in papers occurred around poles 1500 to 1600. The nearest spill-over to the power-house was the main disturbance over twenty miles away.

*Storm of July* 13 *and* 14, *not severe*. A sharp stroke occurred at about a mile and a half from the power house, shattering two insulators on wire B and causing a number of spill-overs on wire C. At a point three miles from the power-house on wire A, there was an uncertain sort of burning in tell-tale which may have been a severe spill-over but probably was not.

At the sub-station the horn arrester discharged in all legs. The electrolytic showed a heavy dynamic burn in leg A, and static in leg C. The low equivalents showed nothing. At the power house the low equivalents showed small burns in legs A and B, and the horn in B, with static in A and C.

*Storm of July* 19, *distant from line.* There was considerable quiet static near the center of the line and many of the lightning rods showed small punctures, as did the overhead ground wires. There were however no spill-overs and no arrester discharges on either end of the line. This storm was said to be distant. Some of the punctures in the lightning rods are given as over 0.04 in. in diameter. They must have been caused by repeated discharges of very small magnitude.

*Storm of August* 1, *distant from line.* This storm was similar to the last storm except that the lightning was distant to the west instead of to the east. There were no spill-overs and no activity in the lightning rods nor in the overhead grounds. None of the arresters discharged.

*Storm of August* 4 *and* 6, *severe, parallel to line.* This storm was very severe at a point about 14 miles from the sub-station, and showed almost no activity at any other point, except that through the central portion activity was evident but in no very great violence. There are one or two doubtful spill-overs recorded nearer the sub-station. Except for a good clear static puncture in the ground connection of the power house horn on leg C, there was no discharge at the power house. At the sub-station, on the other hand, there were discharges in all legs of the horn arrester; in legs A and B, small in volume but perhaps as large as the 5,000 ohms series resistance will permit, and very numerous; and the tell-tale paper was nearly burned up in leg C. The electrolytic at the sub-station showed static in leg A, a small amount of burning in leg B, and also a second static discharge, and no discharge in leg C. The low equivalent at the sub-station showed a discharge of fair size in leg C, but no burning. The Hugo arrester showed discharges in the first gap in all legs, and in legs A in addition a heavier discharge in the next gap which has a less series resistance. The Hugo arrester is only three-quarters of a mile from the nearest severe discharge, occurring on leg A, which is the leg on which the discharge in the second arrester gap at Hugo occurred. This case is a good example of how quickly the energy of a traveling wave can lose its intensity.

*Storm of August* 8 *and* 15, *severe, parallel to line.* This storm passed from the sub-station up the line but was not severe. There were a few scattered spill-overs but no broken insulators. One heavy discharge occurred on leg *C* at pole 1434, about 7 miles from the sub-station. At the sub-station the horn arrester discharged in all legs and held dynamic current in leg *C*. The only other indication of holding of current on any other leg is at the power house in leg *A* in the horn. Discharges occurred in all legs in the Hugo arresters and in one case in all three gaps. This suggests that the test on the arrester is more severe when there is no spill-over; this seems reasonable, for the line then has no relief at the point of attack. At the power house the horn discharged in all three legs and held a little in legs *A* and *C*. The low equivalents discharged in the power house in leg *C* and held the arc a little in the series gaps; static only appeared in the shunt. The electrolytic discharged at the sub-station in leg *B*.

*Storm of August* 18, *very severe—parallel to line.* This storm passed up the line just as did the previous one and had a severe spill-over at a point about 10 miles from the sub-station and another at about 19 or 20 miles and a small one at 12 miles from the power house. At the sub-station the horn arrester discharged in all legs, the electrolytic in legs *A* and *B*, and the low equivalent in leg *C*, series and shunt. The electrolytic seemed to hold a little generator current. The Hugo arrester discharged in all phases in the first gap and in the third gap on legs *A* and *B*. At the power house discharges occurred in all legs in the horns and the low equivalent.

*Storm of September* 6, *not severe.* No spill-overs occurred on the line except two or three near the center. There were numerous quiet static puncturings throughout the length of the line. The only arrester activities were at the sub-station where quiet disturbances occurred in legs *A* and *B* on the horns, in leg *C* on the electrolytic, and leg *A* on the low equivalent. The storm was to the east of the sub-station and not directly on the line.

The remaining storms can be briefly summarized. On the 16*th of September* a storm crossed the line at the power house and caused two shutdowns. All legs of all power-house arresters discharged in all gaps, and there was one spill-over on wire *C* near the power house, within a few poles of the end of the line. The horn showed hold-over current in all legs, the low equivalent in only leg, *B*, and not much there. At the sub-station discharges occurred in the horns in legs *A* and *B*, and in the electrolytics in legs *B* and *C*. There was one discharge in each leg at Hugo.

On September 18, spill-overs occurred on all wires about six or seven miles from the sub-station. Discharges occurred in the sub-station horns in all legs, and in the electrolytics in legs *B* and *C*. No other discharges on the system.

On September 19, a storm 11 or 12 miles from the power house caused a discharge in all three phases in the horns in both stations and in phase *C* at the Hugo arrester. No other discharge occurred.

*General*. An examination of tell-tale papers shows that the sub-station horn with 5,000 ohms resistance in series showed only very fine punctures, showing great limiting of discharge. The horns at the power house having about 500 to 600 ohms of series resistance, and all the low-equivalent arresters, showed considerably larger punctures indicating a freer discharge, while the electrolytic would probably show a still larger puncture except for the fact that the charging current to the arrester itself, which usually follows the discharge for a few moments, burns the paper and enlarges the static punctures, so that it is nearly impossible to determine the size of the hole made by the static. Of course, a holding of the generator current will mask the static punctures; this often happened with the horn arresters as well.

It seems highly probable from the data as to the discharges of arresters that the sort of disturbance making the heaviest demand on the station arrester is the stroke on the line which is nearly but not quite sufficient to cause a spill-over. This disturbance may send a wave the length of the line sufficient to cause arresters to discharge, but not severe enough to be more than the arresters (in this case at least) could handle. These waves go far but they are not enormously severe. This is an important conclusion. The cases in which a much more severe attack on the line causes a spill-over does not send as severe a wave to the station apparatus as the latter type. This is natural as the spark once established to ground will readily discharge most of the severity of the disturbance which would not have been able to get to ground without the actual establishment of a ground arc. Exception is here made of course to the direct stroke of great severity at the station which still remains the most dangerous of all lightning attacks. It is interesting to note that the storm of September 16, occurred at the power house and that no damage was done to apparatus, though the arresters showed vigorous action in all gaps. This could not have been a very severe disturbance.

The arresters seldom if ever, during this season seem to have been put to the limit of their ability to care for the discharges. In no single instance on any one leg did all the sub-station arresters of various kinds discharge at the same time in all gaps. The Hugo arrester discharged in all three gaps only once and then in only one phase. At the power house, omitting the storm of September 16, which occurred at the power house itself, there were only three cases where all the available gaps on any leg discharged, and in one of these cases the severity of some of the discharges was not the maximum. This is important, and is part of the evidence tending to show that the waves coming in to the station (omitting again the direct stroke at the station itself) are not of enormously great volume or energy or voltage and can be properly handled by non-arcing arresters, even of the series resistance type. This conclusion is of the greatest importance, and seems very well substantiated by the data of this paper. Of course, the insulation of this line is not as high as can now be obtained through the newly developed insulators on the very high voltage lines, so that more severe waves must be expected to appear at the stations in some of the systems now building, but the principle is the same and additional insulation strength can if necessary be given to station apparatus and circuits.

From this line of reasoning; namely, that the limit of discharge capacity of the arresters was not reached, it may be concluded that the so-called sensitiveness of discharge, at least as between the arresters installed in this plant, is of relatively no moment. Since the arresters have been able easily to care for all discharges, and since they have discharged often but rarely if ever to their limit of capacity, any greater sensitiveness would add nothing. In fact the less sensitive the arresters the better, as long as protection is secured. A certain risk is run every time that an arrester discharges, and they should act only when necessary to protect the line. The quality most requisite is the freedom of discharge. Furthermore, any degree of sensitiveness may be obtained by the proper setting of the initial gap and any arrester can be set as sensitively as necessary, provided only that it still remains non-arcing.

The following is a summary of the relative action of the various arresters during this season:

| At the sub-station | Discharges. |
|---|---|
| Horns without low equivalent or electrolytic | 12 |
| " " " " | 21 |
| " " electrolytic | 15 |
| Low equivalent with electrolytic | 2 |
| " " without " | 6 |
| Electrolytic " low equivalent | 12 |

It thus becomes evident that the horn arrester is here set to be the more sensitive and always responds, and that if either one of the others starts it prevents a discharge in the third. It must be noted that no direct discharge on to the line occurred near the sub-station.

| At the power-house. | Discharges. |
|---|---|
| Horn without low equivalent | 7 |
| " with " " | 10 |
| Low equivalent without horn | 2 before<br>resetting. |

The same conclusion follows here as from the sub-station data.

It is probable that the horn arrester when using series resistance is not a free discharge but that either of the other types were, since they would seldom discharge together.

As to non-arcing power, it may be said that the horn with resistance and the other types were non-arcing on this plant which has a relatively limited power behind it, but that the horn without resistance was not non-arcing. This is as expected, and is shown by the numerous records of the opening of the circuit breakers.

*Shattering of insulators.* This is a most important and instructive study. Out of forty-two injured insulators only three were punctured. The others were shattered, that is, had their petticoats cracked or broken without any direct puncture of the porcelain. The cause of this phenomenon, at least in the case of these results, must be taken to be the shock of the static and not at all the effect of the generator arc, as is frequently supposed, for in the storm of July 4 there was no power on the line and eight insulators were shattered. This shattering sometimes does and sometimes does not cause a shutdown. This direct shattering of insulators without puncturing by the lightning is startling and undoubtedly indicates that the discharge is very abrupt and violent, it further indicates the difficulty of testing insulators for actual service conditions by laboratory apparatus. In addition to the 39 shattered insulators there were nearly 150 spill-overs that did not cause injury to the insulators. Inspection of tell-tale papers shows that these spill-overs were often just as severe in many cases when no injury was done the insulator as in the other cases. Although the data in the paper do not enable a conclusion to be definitely drawn, it seems true that many of these spill-overs occurred without shutting down the plant.

From the general appearances of the disturbances it seems a fair inference that, while the number of spill-overs was undoubtedly increased by the presence of the ground wires to the pins, there would have been many such discharges in any case. This view is supported by the breaking of insulators in the storm of August 18, when there were six insulators shattered in a section of line where the ground connections had been removed. A most important result follows from such a premise. If the discharges that are to be expected are irresistable and are going to ground in any case, then the great cost and mechanical complication that is proposed for many high voltage plants may fail to serve the purpose expected. And also a second most important conclusion—which is nothing but common sense and has already been sometimes recognized—every insulator should be so constituted as, when subjected to an irresistible potential, always to fail by discharge over its surface and without cracking, for then often little or no inconvenience or delay will result, while if the insulator is broken or punctured, an interruption and long delay for repairs may result. This point cannot be too much emphasized. This ideal condition seems to have been pretty well realized at the Taylor's Falls plant as far as freedom from insulator puncture is concerned. If each spill-over had been a puncture it is easy to see what a serious menace it would have been.

*Character of individual discharges.* A careful examination of the distribution of punctures and spill-overs indicates with considerable certainty that a given disturbance attacks the line at a very definite point and may either go over or through an insulator to ground, or if unable to do this to pass along the line to find a weaker spot or to wear itself out. It is certain that such a discharge, at least in this plant, will pass by at least three to six ungrounded poles to go to ground over a pole with a grounded pin. These pin grounds occur every third pole. This means that the front of the static wave does not drop as much in potential along the line for three poles as the difference in the insulation strength between the grounded and the ungrounded poles. On the other hand, the wave will not pass by, perhaps ten poles, to discharge over one of the grounded pin poles. This indicates that the drop of potential in the wave front is greater in the ten poles than the difference in pole insulation strengths. The latter data come from the storm of August, 18 where six insulators on ungrounded poles were shattered within less than ten poles of grounded pins. In other words, not more than a thousand or at most a few thousand feet of the wave front will have travelled by an insulator before the maximum or at least the spill-over point is reached. This steep wave front corresponds to a very high frequency. It is well to notice in this connection that the feature that is of importance is the steepness and magnitude of the wave front of the initial discharge and not the frequency in the usual sense as is generally assumed In rapidly decreasing oscillations such as characterize static discharges, if a break-down does not come at the first wave it is not likely to come at all. There can be no proper frequency unless there are several complete cycles established and the formulas for steady alternating currents do not apply even momentarily for the initial wave front.

Damage due to a given storm is not usually limited to a few poles, it is limited but may often extend over a mile or two of line. This indicates that in a given stress locality there are a number of more or less individual discharges due to the same general conditions yet separate in space and perhaps a little in time. This conception seems very reasonable.

It appears to the writer that the spill-overs that have been here considered are largely due to direct strokes, major or minor, actually reaching the line wires. Not necessarily all of great magnitude, such as the strokes that are visible for miles, but large enough perhaps for discharging a relatively small area or volume of air, even only a few hundred feet in extent. This seems almost an inevitable conclusion from the Taylor's Falls data since the lightning rods several times showed tell-tale punctures in the ground connections exactly similar to the punctures in the pin tell-tale papers. These lightning rod punctures could not be due to released bound charges as the static capacity of the rods is too small. It is further hard to conceive of such concentrated discharges as are shown being due to induction from a distant cloud. Again it is difficult to see how enough energy can be stored in a short length of line wire such as seem to take part in most of these disturbances to do the damage that is manifest in the actual case. For these reasons and for others the writer considers these data strongly to confirm his previous opinion that disturbances of the general nature of these shown here, which are almost universal in transmission lines, are due to direct discharges of electricity at high potential out of the atmosphere onto the line wire.

A careful study of all the tell-tale papers in relation to their phase relation and their position on the poles shows that in a large majority of cases of isolated single spill-overs, the top insulator is not the one affected. The fact is marked when the total number of the specific instances recorded are considered. This has a most important significance, for it can indicate only that the charges approach from the side before the actual discharge rather than from the top, straight downward. On consideration this seems to be the natural course, for although any gradually approaching source of disturbance will tend to come downward gradually, yet at storm times there are always strong currents of air along the ground which would certainly overbalance any downward motion. Downwardly moving air can have no place to go without passing to the side after reaching the earth, so that it is extremely probably that the course of the air will always be along the ground with a slightly upward or downward motion. This means that the chances are that the side wires as well as the top wire will sometimes be reached by a discharge. Of course, this does not mean that the top wire will never be struck nor that the same exact phenomena will be found everywhere else as in this case, but in such matters as the locating of ground wires this possibility must be clearly borne in mind.

Furthermore, in some eight or ten cases of the most severe discharges the same pole shows spill-overs on all line wires, one of which (usually a side wire) is generally much lighter than the other two. This suggests the probability that, after such a very severe discharge has jumped onto one or two of the line wires, their potentials are so raised that they cannot contain the discharge and it jumps to the third wire. This will be of course on account of the impedance in the ground path. This does not seem perhaps a remarkable conclusion but it leads to an important inference, namely, that if overhead ground wires are to protect they must be so far spaced from the line wires as to prevent a discharge thereto. It is evident that the power of these overhead ground wires to carry a discharge to ground and prevent its jumping to a line wire will depend on the nearness of its ground connection to the point of attack. With such discharges as have been found in this case, which are undoubtedly typical of most plants, a ground connection more than a few poles away would be entirely inadequate. It is not so necessary that this ground be a perfect one, as to some extent any local rise of potential at the ground connection at the foot of a pole would tend to protect the line wires on the same pole.

*Origin of lightning.* Before summarizing the above discussion, it will be interesting to speculate a little about the nature of the phenomena in the clouds from which these disturbing actions come. According to a recent hypothesis, the rise of potential in the clouds is as follows: by some cause, perhaps the action of the sun's rays, there is produced a more or less gradual ionization of the air in certain strata of the atmosphere some distance above the earth. This produces electrons, (or negative charges) and positive ions, (which are loose atoms of matter with a positive charge). At the same time there is usually an accumulation of water vapor in the locality. It is known by laboratory experiment that at a certain pressure, water vapor will condense on electrons. Whenever the necessary pressure of water vapor is reached undoubtedly such a condensation will occur and these electrons, being loaded down each with a drop of water, will fall to the earth or toward the earth, leaving the positively charged ions suspended in the air. This will, of course, raise the potential of the positive charge, the energy for which process comes from the potential energy of the water drop, which it possesses in virtue of its elevation and its attraction by gravity. As this action goes on, there is produced a higher and higher potential of positive electricity built up by the step-by-step withdrawal of the electrons by weight of the condensed water vapor It may also be assumed that the water vapor goes on increasing in pressure in the upper region until finally, at a much higher pressure than before, the vapor begins to condense on the positive ions and they also then come down gradually.

Now as the two charged layers of air, positive and negative, will usually be widely separated by the wind and other agencies, there will exist throughout the region, charged bodies of air or mist which are some positive and some negative, the negative getting to the earth first or being carried to some other point, while the positive electricity (the usual polarity of the clouds) remains.

When, however, any two of these highly charged bodies of air of opposite sign come into the same neighborhood, there will be a discharge between them, if their potentials are high enough. This will be the well-known lightning in the clouds. Or if a positively charged region does not find an opportunity to discharge to a negative region in the air, it will gradually approach the earth and then discharge to ground.

Suppose that at the end of a hot day a highly charged layer of relatively cold and heavy air has accumulated above a warmer uncharged layer below, which has been heated by contact with the earth in the sunlight, much as a layer of oil may be made to support a layer of water above it, momentarily. The equilibrium is evidently unstable and the layers will overturn at any opportunity. When this process starts the cool air will break through the lower layer of hot air and the whole cold body of air, which is heavily charged electrically, will come to the earth at some point while the hotter uncharged air will move to one side and upward to make way for it. This action suggests the cold breeze which so often accompanies a lightning storm. In this case, of course, all the charge of the air will be discharged into the earth at or near the point at which it breaks through the warm layer either in a few heavy strokes, or, more likely, in a few heavy ones and a great many smaller ones, ranging all the way in size down to brush discharges to earth or accumulations of charge on a line, where there is not enough power to make a direct discharge.

Now this hypothesis accounts very nicely for the tentative assumption that a number of relatively severe flashes occur in one immediate neighborhood, practically simultaneously but not identical and not in exactly the same position. There is a large bulk of air to discharge and each discharge relieves only its own immediate region which is accessible to its discharge path. Other regions in the neighborhood may have no discharges at all, for the cold or charged air has come down only at a relatively few places. There would presumably be other more or less distant locations where the upper cold air layer would break through again and repeat the phenomena.

It is interesting to note that the effect of these ions on the air where a discharge is imminent, especially in the upper air, is greatly to reduce the jumping voltage of the intervening distance. This is the well-known action by which one arc will start another, and indeed is the process by which the arc itself is maintained when once started. It is the presence of the ions and electrons in the arc path, which allows the normal voltage to maintain an arc which may be so much longer than the distance that normal voltage will jump in the first place. If it be assumed that the number of ions in the upper air be considerable, this may mean that the jumping distance through the air in the region may not be so very much greater than the arc-holding distance. This would go far toward making the great length of many lightning strokes seem reasonable, especially in view of the generally accepted hypothesis that the long discharges are progressive, that is, made up of a great many shorter ones, following in quick succession. All the above discussion is purely speculative, but it helps to give a concrete idea of actions that are regularly observed.

*Summary.* The net result of these various considerations may now be summarized. The Taylor's Falls system as here reported was disturbed from time to time in particular localities along the line by lightning. In each such locality, the extent of which rarely extended over more than a mile or two, there were usually several more or less severe discharges which struck the line wires from the atmosphere. These charges when relatively mild charged up the line and sent waves of static in both directions along the line without spilling over. These waves though of diminishing volume were able to pass many miles and still cause arresters to discharge at the stations. These waves, however, were entirely within the power of the standard arresters at the stations to discharge to earth. This must inevitably be the case since the wave energy has to be carried along the line and by the capacity of the wires and the insulation strength of the insulators.

When the discharges striking the line are too severe for the insulators to withhold, however, they pass over or through the insulator to earth. This may or may not cause a shutdown, a fractured insulator, or an injured pole. In the great majority of cases here reported none of these resulted, unless it may be that shutdowns were frequently brought about. The data are not quite complete on this point. In going to earth these discharges will choose a path to earth not more than a few poles from the point at which they reach the line. They will exert a preference for the weakest of the two or three nearest poles, provided the difference in insulation strength is great, but they will not go much farther for a ground, probably even for a dead ground.

Also in this case in which spill-overs occur, waves of static are sent in both directions along the line but in view of the discharge to ground at the starting point these waves are very likely to be of less intensity than the waves produced by discharges into the line not quite severe enough to cause a spill-over. Thus a mile or two from one of even the severe strokes on the line the effect on the system is not especially severe.

The abruptness of the wave front of these discharges is of the order perhaps of that of a periodical oscillation of 100,000 per second, though it may vary through wide limits. Extra severe discharges when they come are almost sure to reach all three line wires at the same point, though it seems entirely probably that, at least in this plant, the discharges from the air do not strike directly downward but come in from one side or another.

In this district the discharges striking the line were sometimes very severe, so severe that they jumped freely to earth over insulators, cross-arms and poles, and with such static shock as to crack off petticoats in the absence of generator current.

Little protection is obtained from lightning rods located beside the line. Whether protection will be obtained from overhead grounded wires or not depends entirely on the arrangement of wires, the frequency of grounding, etc. Station arresters of the best types should, in the absence of severe discharges close to the station, protect adequately the station apparatus if properly insulated.

Horn arresters as here installed with some paths to ground without adequate series resistance, are not non-arcing and can be relied upon occasionally to shut down the plant. On the other hand, both the electrolytic and the low-equivalent arresters showed themselves properly non-arcing and caused no trouble on this score. The size of punctures in tell-tale papers produced by the discharge of one of the *waves of static* after passing along the line in the worse case does not exceed a very few hundredths of an inch in diameter, while the disturbances striking the line directly caused enormously greater punctures in the pin grounds, sometimes measuring an inch or more.

The above conclusions apply strictly only to this line and to this particular season, but it is evident that the nature of the phenomena must be essentially the same in most cases; and by making a common sense allowance for different conditions and different numerical values of voltage, insulation strength, capacity, etc., the present results can be applied to almost any high tension line.

In the operation of any high-tension system, it should be a strict rule to record and analyze all important breakdowns, use tell-tale papers and other recording devices where practicable, and to require reports of observed conditions and otherwise to arrive at the actual nature of the disturbances at the particular plant. This method of procedure though irksome, especially at first and if not systemized, will go far in the long run toward obtaining the most satisfactory operation. The educational effect on all persons concerned is in itself very valuable. Further, it forms a basis for future review of the situation should that become advisable.

## DISCUSSION ON "MEASUREMENTS OF LIGHTNING, ALUMINUM LIGHTNING-ARRESTERS, EARTH RESISTANCES, CEMENT RESISTANCES, AND KINDRED TESTS", "TESTS WITH ARCING GROUNDS AND CONNECTIONS", "CRITICAL STUDY OF LIGHTNING RECORDS ON TAYLOR'S FALLS TRANSMISSION LINE."

ATLANTIC CITY, N. J., JUNE 30, 1908

**J. F. Vaughan** (by letter): It is gratifying to have a careful, independent analysis of the Taylor's Falls lightning records such as Mr. Thomas has given in his paper, and interesting to see wherein his conclusions differ from those of the original papers on this subject.

The main idea suggested by Mr. Thomas' paper, that the more pronounced disturbances at least have been due to some form of direct discharge between clouds and line, is fundamental, and requires radical modification of present conceptions of the nature of the direct stroke. It suggests that such a stroke may be:

(1) Of length varying from a few feet upward.

(2) Of quantity and intensity varying from a relatively small disturbance to a destructive bolt.

(3)* Of such a nature as to distribute itself with considerable uniformity over sections of line and overhead ground wires.

(4) Of frequent occurrence, amounting to hundreds of strokes during the season.

The main objection to the "Release of bound charge" theory is that the capacity of the line is not sufficient to account for the volume of discharge indicated by the tell-tale records. However, the potentials and rates of discharge may be sufficiently high to compensate for the relatively small capacity. There is little evidence of any great amount of energy in the discharges, even in the shattering of insulators, providing a high enough rate of discharge is assumed.

There is, however, ample evidence of extremely high velocity of disturbances in the rapid damping out of potential in the line, the mechanical nature of the insulator fractures, the activity of line choke-coils and the splitting apart of the laminations of the tell-tale papers.

In the discussion of overhead ground wires, Forms A and B, the records of storms of July 4 and August 18 are not considered as showing definite protective power. By reference to the original curves (Fig. 12 of the writer's paper) the record of the storm of July 4 shows by the activity of overhead ground wires A and B that the latter were well within the active area of the storm. If the curves representing line-insulator stress and overhead ground-wire discharge are added together, this fact will be evident. The curves for the ground-wire sections on each side of the storm center show that as the center is approached the activity of the sections increases rapidly, with no corresponding increase of stress in the line insulators until the unprotected section of line between the shielded sections is approached within a few hundred feet; that is, the shielding effect of the wires appears to be pronounced even to within a few hundred feet of their ends. The storm of August 18, which was reported as the most severe for years, was active over ground wire B. Although the discharge from the ground wire was considerably larger than in any of the other storms, the average disturbance in the line shielded by this construction is shown by the curves to be low compared with those of unprotected sections in other storms. Over the central portion of this section of the line there is only one heavy spill-over, and as that is within less than 1000 feet from the end of the ground wire it may have come in from the adjacent unprotected section.

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* See original paper by J. F. Vaughan, Fig. 12, curves of July 4.

Mr. Thomas calls attention to the probability that the side transmission wire toward the direction from which the wind blows is probably subject to more disturbance than the other wires. This exposure is shown in the general graphic chart by greater activity in the wire toward the approaching storm, excepting where the storm is overhead and near enough to cause spill-overs and physical damage, in which case the top wire seems to be the one most subject to trouble.

In interpreting the curves the following should be borne in mind:

(1) That the lower ranges of the scales of ordinates adopted for plotting the curves are exaggerated in order to show the smaller values more plainly.

(2) That the discharge paths of the shielding-device grounds are freer than those of the line, and the discharges being consequently less disruptive, are probably quantitatively greater than the line discharges for given sizes of puncture.

(3) That the sections of shielding wire are not long enough to insure the damping out of charges coming in from adjacent unprotected sections within the length of each shielded section.

In connection with the direct-stroke theory it is interesting to note that no clouds have been observed sufficiently low and close to the line to account for short direct strokes. Nor have any spill-overs been actually seen. Close watch is being kept on the line this summer to get information on the appearance of clouds and line during spill-overs, and the nature of insulator breaks is being further studied.

**Charles P. Steinmetz:** While some years ago the problem of electrical-power transmission and distribution, in its stationary condition, was already very well developed in most of its features, there always remained this class of phenomena, of which lightning is characteristic, which we may call transient phenomena; that is, phenomena which last only a short time, frequently an extremely short time, but which are of such a character that the damage they may do makes up entirely for their short duration.

We are approaching a clearer understanding of these phenomena and also a control of them, so that it looks not improbable that in a very short time lightning, and all these disturbances in transmission lines and transformers, will have lost their danger to us; that we will be as familiar with them as with the design of an alternator or of a motor, and that we shall be able to predetermine, control and eliminate them.

I am particularly glad myself to be able to see how the consensus of opinion of those engineers who are studying the subject most deeply is coming around to what I have maintained so many years, that the most effective protection of the transmission line is through overhead grounded wires. Some years ago, very few people agreed with that statement, now we find that most of them agree with it, and even these few doubting Thomases will, I hope, be convinced.

I believe to protect an electric system efficiently and effectively it is necessary to protect the line and protect the stations. We cannot expect to escape damage, no matter how complete the protection we install in the station, if we leave the transmission line unprotected. Neither is the protection of the line alone sufficient; but what I believe we can already, at this time, state in with fair certainty is that if the transmission line is well protected by overhead ground wires, whatever disturbances we get will not be so severe that we can not take care of them safely by protective devices in the station.

I do not quite agree with Mr. Thomas in explaining the disturbance in the Taylor's Falls transmission by direct strokes; or rather, to explain it more fully, I do not see an essential difference between a direct stroke, as described there, and the phenomenon of the bound charge of lightning.

Let us see what happens in a direct stroke. If the potential difference between the line and cloud rises so high that somewhere in the field the potential gradient exceeds the breakdown strength of air, a breakdown occurs, as a discharge from line to cloud, or into space, thus equalizing the potential. In the other case, if by a discharge in the clouds the potential diference between the clouds and ground is suddenly changed, the bound charge of the line is set free, and that means that suddenly upon the line a very high electrostatic potential is impressed which discharges from the line into space, if the voltage is beyond the disruptive strength of the surrounding space. In either case—whether this potential difference is created by a discharge into the cloud, setting free the bound charge, or whether it is created by potential difference between the cloud and ground—if the voltage is high enough, the discharge passes from the line into space, toward the cloud. I thus do not see how we can distinguish the phenomena of the bound charge from the phenomena of the direct stroke, but believe these two phenomena are practically the same.

There is only one point I want to mention, and that is to express my regret that in the tests and investigations valuable records have been lost by the combustion of tell-tale papers. These tell-tale papers can be protected by fireproofing, and I bring that to your attention, because it can easily be done (and it is very desirable to do it) by treating these papers with a solution of sodium tungstate (also called sodium wolframate). They become fireproof by such a treatment, and there is no longer danger of losing them or setting fire to them. A quarter of a pound of the sodium tungstate bought at any wholesale drug house, is dissolved in a pint of hot water, and the tell-tale papers immersed in that solution, and then dried. There is no apparent change, except that the paper is slightly rougher. You can write on it the same as before, the lightning discharge makes the same markings, the same punctures appear in the tell-tale paper, but it cannot be set on fire, the flame cannot consume it, and therefore you cannot lose any of the papers by fire. I believe it is very desirable to carry out this precaution. I do not know that there is anything else to add, and I thank you very much for the opportunity of expressing my opinion on these papers which have been presented.

**P. M. Lincoln:** I agree with Mr. Steinmetz that the most important question raised by the lightning-arrester papers is that of the ground wire, and I will take issue with Mr. Thomas in his interpretation of Mr. Vaughan's results which were presented to the Institute at the last meeting. In my own interpretation of Mr. Vaughan's results, I found to my satisfaction that there was a very marked protection given to the line at Taylor's Falls by the presence of the overhead ground wire.

Possibly I have not given this matter quite such close attention as Mr. Thomas has, but I would like to have him detail, if he will, the reasons why, and how he can draw conclusions to the contrary.

I would like to ask Mr. Creighton, too, whether or not the records obtained by him in Figs. 3, 4, and 5 were obtained with current on the line, or whether the line was dead at that time. I presume there was no power current on the line at the time the records were taken, judging by their shape. I would also like to ask Professor Creighton for his opinion as to the efficacy of the overhead ground wire.

**A. E. Kennelly:** Overhead wire protection is a matter of very great importance on account of the radical nature of the construction which it involves. This matter is one concerning which experience of some kind has been gained for more than fifty years; that is to say, ever since overhead wires have been put up for telegraph purposes there has been the same trouble with lightning, differing only from the trouble that transmission engineers have had, in the fact that the poles were ordinarily not so high as at present, that the insulators were very much weaker electrically, and that instead of having a high-potential dynamo at the end of the circuit, there was no appreciable power on the circuit. Nevertheless, the damage done by lightning was recognized at a very early date. Apparatus was burned out, insulators were destroyed, poles were smashed or damaged.

It was found that the lower wires largely escaped. I think that is the consensus of telegraph engineering opinion all over the world. The upper wires bear the brunt of the damage. Poles were found to be saved in very large measure by putting grounded wires on the poles themselves, putting a lightning protector on each pole. The upper wires were not grounded every half mile, as is customary with protecting wires; but nevertheless the protection from overlying wires grounded at distant stations was found to be material, although incomplete.

In my opinion we shall never have any system of absolute and complete protection against lightning, even with the best devices that we can install in the station, or the most perfect system of overhead grounded wires that we can devise. We can hope with care to minimize the damage due to lightning, but we shall always have some trouble left. Anyone who looks for a panacea against lightning is entertaining a very courageous expectation, which is likely to meet with some discouragement.

I think that we ought not to attempt to form too definite a conclusion as to the source of lightning disturbances upon the wire. Mr. Thomas intimates that the disturbances are mainly due to little direct strokes, but others think, from the same records, or with the same data before them, that the disturbances are due to the release of bound charges; while still others think they are due to inductive disturbances. There are so many possible causes for disturbances that we should hold our minds open and not consider that everything is due to one and the same source of injury. For example, in the case of an overhead wire, we all know that there is a movement of electrified air over the wires conveying electrical charge to them continuously. Secondly, we have the release of bound charges, and thirdly direct strokes. Fourthly we have a source not generally recognized, namely, electromagnetic waves. If over a distance of several miles there can be produced in a wireless telegraph antenna a received e.m.f. of fifty or one hundred volts from a small alternator at the generating station, surely a lightning discharge with its enormous generating power is able to produce electromagnetic-wave disturbances in long wires of very much greater magnitude.

It seems, therefore, that we should not try to formulate a rule and declare that all disturbances due to lightning in overhead transmission wires have one and the same origin. We must expect, with a number of disturbances, that a number of different kinds of apparatus may be necessary to be installed, some to protect against one kind of disturbance and others to protect against other kinds of disturbance.

**John B. Taylor:** Professor Creighton has shown his ingenuity in devising special pieces of apparatus to determine what is actually going on in a transmission line. We wish to know what we have to guard against, and I think that papers of this sort are more to be desired than many we have had in the past. The conditions of operation are so variable that some conclusions drawn as to the better of two types of arresters are not justified; but when we know what we have to deal with, and to a certain extent can duplicate the conditions in the laboratory, we can begin to produce apparatus which will meet the requirements.

I have not had a chance to give this paper as critical reading as I would like, but there is much confusion in my mind over the use of the term "lightning." I do not know why the word lightning should be applied in a new sense. The word has been in use for many years, and almost everybody in the profession, and out of it, has a pretty definite idea of what the term signifies. Professor Creighton, apparently, wants to call anything abnormal on a transmission line "lightning." When he speaks of the natural frequency of lightning, does he mean the natural frequency of the lightning stroke from the clouds, or the natural frequency of the discharge of the line, with which he is experimenting, to ground? The records show mainly frequencies of three thousand cycles, or in that neighborhood, and as I read the tests, this frequency is merely the one at which the particular line discharges to ground, and gives no indication of the frequency of the lightning discharge itself. The variation between 3,000 or 4,000 and 15,000 may be due to the distances out on the line at which the lightning discharge proper occurred. I trust he can give us a little defense of this use of the terms, because to my mind it has made a good deal of misunderstanding in reading the paper.

Reference is made to a further analysis showing in addition to 3,000 cycles or thereabouts, superposed higher oscillations of a million cycles. I believe he used the term lightning as applied to these million cycles. How can a lightning stroke a mile or more in length be expected to oscillate with a frequency of a million cycles? A stroke a mile long, with a period of oscillation of one million cycles, would mean a velocity of at least one million miles per second, whereas the known velocity of light and electrical impulses in the ether is only approximately 190,000 miles per second. Does the apparatus demonstrate this high frequency in the lightning stroke, or is it the period of parts of the test line and apparatus—a secondary effect of the lightning?

The data given on actual resistances of ground connections are valuable. The putting in of these ground connections goes largely as a matter of chance, and more perhaps as a matter of faith. We put up an expensive equipment of lightning arresters—and then run some kind of a wire into the earth, and seldom make tests to determine whether the latter is effective or not.

From one test, a value of 30 to 40 ohms is given as the actual resistance of the ground itself between two points several miles apart. I think there must be some mistake in this, as judging from a test made in dry rocky soil, the resistance of the earth, apart from that at and near the contact plates, is not likely to be anywhere nearly so high. Was this measurement made with alternating or direct current?

Mr. Berg gives us figures from tests of practical value, because the arcing ground unfortunately occurs at times on transmission systems. Mr. Berg does not offer any explanations as to the cause of this excess potential, and possibly in discussion he may give us his idea of it.

What appears to be the simplest explanation of this excess potential, as evidenced by the needle gaps, is a compensator or auto-transformer action in the transformer itself. The windings of the transformer have electrostatic capacity to ground, which capacity is not evenly distributed along the winding, but is greater in some parts than in others, giving an arrangement equivalent to condensers connected between points of the winding and ground. Considering one of these condensers near the terminal where the arcing ground is to take place, this condenser will become charged to a high potential, and as soon as the gap to ground breaks down, the charge will pass through a small portion of the transformer winding, stepping up the voltage at the other terminal of the transformer. Where two transformers are interconnected in an open-delta arrangement, the normal potential of one transformer is added to this excess potential derived through compensator action in the other transformer. This might explain why one line terminal in the open-delta arrangement shows higher voltage to ground, by needle gap, than the other line terminal.

In practice, of course, the action is not as simple as this, on account of the complex nature of the distributed capacity, reactance of winding, losses in iron core, etc., but this explanation of the phenomenon seems to be a simple, rational one.

One word more on Mr. Thomas's paper. I want to take issue with him on his choice of terms. I cannot understand why the term "static" is used here to represent anything but a static condition. In the old days we had "static" electricity and "dynamic" or "galvanic" or "voltaic" electricity, and the study of static electricity had to deal with the distribution of charges on bodies of different shapes, the forces of the attraction and repulsion between bodies when they were charged, and similar matters. The term "static" applies to a condition of rest. Now we seem to use the term to call to mind anything but a condition of rest. The term has crept into this use in the last few years and I hope we can find some other word which will more truly represent the condition of affairs, and not upset a term which already has a well-recognized use in the older books.

**R. H. Marriott:** In the territory in which Mr. Creighton was making his tests there were several wireless-telegraph stations from 1905 to 1907. At these stations we had a great deal of trouble with what is called "static." There were four stations: one at Pueblo, one at Altman, one at Colorado Springs, and one at Denver. At the Denver station were two masts 200 ft. high and 300 ft. apart, with a station house half-way between. One aerial consisted of a flat-top loop in the same plane with the masts, and stretched across the top of the masts with the ends in the station house. Another aerial consisted of forty wires suspended from a cable, and in planes at right angles to the plane of the masts. The highest point reached by the forty wires was about four feet, directly below the flat portion of the loop. The relation of the flat-top loop to the forty wires was in some respects similar to the relation of the grounded overhead wire to a transmission line.

On a test made between points to ground while a thunder shower was approaching, the maximum discharge from the forty wires was approximately 2 inches long, and the maximum discharge from the flat-top loop was approximately 2½ inches. We accounted for the greater discharge from the loop as due to the fact that it was higher in the air than the forty wires.

At all the Rocky Mountain stations the wire that extended the highest in the air gathered the most static, as indicated by the wireless receiver, even though the natural frequency of that wire was greater or less than that of the lower wires.

There were about three months of the year 1906, June, July, and August, when we had bad static practically all the time, except between 3 a.m. and 6 a.m. The natural frequency, *i.e.*, the number of alternations in the discharge itself, was apparently at times about 1,000,000 cycles—so estimated because the tuner was set frequently at 300 meters, and the static impulses were received better on that tuning than on others. The tuner consisted of variable inductances and a fixed condenser. I should say, from my experience with these static discharges, that they were sometimes as low in frequency as 50,000 cycles, and sometimes as high as 3,000,000 cycles per second. The discharge frequency, that is, the number of sparks at Pueblo, on one test from a seven-wire, 200-ft. aerial across a 3½-in. spark gap to ground, was one spark per forty seconds, whereas across a ⅛-in. gap, a discharge took place about every one-half second.

We accounted in different ways for the static which troubled us. One explanation was that a discharge took place between a cloud and the earth, or between two clouds, setting up electromagnetic waves which traveled out like the electromagnetic waves from our transmitter, and thus set up oscillations in our receiver antenna. Another cause that we attributed the static to was that the air about our aerial had a potential difference to earth, and discharged to earth through the aerial. Another cause was friction of winds on the wires. In our telephone receiver, when attached to the wireless detector, the static makes a buzzing noise, weak static making a faint buzzing noise, and strong static making a loud buzzing noise. The strength of this buzzing during a wind storm increased with the velocity of the wind. This may mean, however, that when more air is passing more charges are carried to the wire.

I have never known of a wireless station being struck by lightning. In one case a report came in of damage to a station due to lightning, but on investigation it was found that the operator, not realizing the conditions, had moved an antenna from its original position and had placed it above and across a 1300-volt line. The antenna guy ropes stretched and grounded the line through the receiving instruments, which acted as a fuse. This occurred at Altman, where lightning is so common and severe in the summer that a description of its activities is almost unbelievable. The aerial here was 160 ft. in height. On one occasion when I was present lightning burned out a transformer situated about 100 yds. from the wireless station. These burn-outs were said to be quite frequent. In Pueblo we had a 200-ft. tower mast at Minnequa Park, in a district in which lightning is said to strike very frequently. This mast, with 16 steel guys, broken by strain insulators, had just been completed, and a steel cable was pulled up about 100 ft. with its lower end lying on the ground. During the night lightning struck a one-story house about six squares away, but there was no evidence that it had struck the mast or any of the cables. It appears to me that the most probable explanation as to why these wireless stations were not struck is that the antennæ served as a path through which the charges above and around the antennæ gradually leaked to earth, thus preventing the accumulation of a sufficient quantity of electricity, at any one time, to cause damage upon discharging. This explanation is based on the fact that the severest static occurs shortly before a thunder storm reaches a station.

**D. B. Rushmore:** Our knowledge of lightning phenomena is constantly increasing, and the operation of lightning arresters is each year becoming better understood. For much of this we have to thank the oscillograph.

Some caution is necessary in interpreting the results of indications caused by the puncturing of a piece of paper. It is possible for discharges to take place over series resistances which puncture paper and which have the optical effect of a considerable discharge, whereas in reality the conditions may be such that but little relief is afforded to a rise of voltage.

A great deal of engineering must be done on more or less inexact knowledge. This is true of the use of a ground wire, where it is difficult to get exact comparisons of operation under the same conditions with and without that protection.

Complete protection against lightning is being more or less closely approximated at present. From the experience which the speaker has been able to gather, it would seem that a transmission line can be practically protected against atmospheric disturbances by appropriate tower design, by the use of one or more ground wires, by the use of lightning rods and by the use of a much higher factor of safety in line insulation than has been customary. With modern protective apparatus, intelligently installed and kept in efficient working condition, it should be impossible to obtain a rise of voltage in that vicinity.

It would seem to be a fair statement to say that we are now at a point where, with the best apparatus installed in the best possible manner, and with the most careful design of transmission lines, practically complete protection against lightning can be had.

**J. W. Fraser:** I want to say a few words commending the work that has been done on this subject, and that has made possible the papers which we have heard this morning. The scope and thoroughness of this work is highly deserving of mention, and I am glad to see such a large attendance, and to find that so many of the members have taken such a deep interest in this work; for it is only by such intelligent and painstaking investigations that manufacturers can obtain sufficiently reliable data to give us an arrester which will be of real service under all conditions.

In the past it has been the practice of the Southern Power Company to install alternately a multigap or low-equivalent arrester, at all its sub-stations, in addition to the grounded wire over both steel and wood lines; and this company installed last autumn and this spring fourteen aluminum-cell arresters, half of one make and half of another, at various points on the lines Several severe storms have passed over different parts of the lines since these arresters were put in service, and they seem to be doing good work. On grounds these arresters have operated continuously for several minutes, apparently with very small variation in the voltage.

Although there are 315 miles of 44,000-volt line with 98 transformers, and 50 miles of 11,000-volt line with 48 transformers in service on the Southern Power Company's lines, most of which were installed last summer, only one transformer has been lost, out of the entire number in operation, from causes traceable directly to lightning. It is to the credit of the manufacturers that this is the case. True it is that a few terminals have been burned off and a few bushings broken, but such troubles are not comparable with burned-out transformers, and show the necessity for a better path to ground than the old arrester.

It has been the intention of the Southern Power Company to make a systematic study of lightning and freak voltages, but so far all that has been done was to keep an accurate log of all disturbances on lines since January 1, 1908. Of the twenty-one lightning storms which have passed over the lines since that time, eighteen were severe and three were light. Out of eight storms there was no damage of any kind. In five storms, a total of about a dozen insulators had either one or two petticoats broken off; in two storms two meters were damaged; in two storms one leg of three 44,000-volt oil switches was punctured; in one storm, one 2200-volt oil circuit-breaker blew up (no current on the transformer and the lightning struck a short secondary about 300 feet long); in one storm, transformer leads were burned off two transformers inside the case; and in two storms the line was grounded through a punctured insulator and caused considerable damage.

The most difficult thing we have to contend with is a grounded conductor. The overhead grounded line and the old form of lightning arresters seem to take care of ordinary lightning storms comparatively well, but as soon as a conductor is grounded, due to any cause, there is sure to be a fire display over the entire system and damage is inevitable. We believe, however, from the experience we have had with the aluminum-cell arrester that this arrester will be of great service in trouble of this nature. Its ability to withstand continuous discharge for some time without varying the voltage materially gives it a place unheld so far by any other arrester A rather peculiar incident happened the night before I left to come to this meeting. I had just read the part of Mr. Creighton's paper that refers to the station grounds, where he cautions every one to couple all grounds, when our superintendent of construction came in and related an experience he had had that day bearing out Mr. Creighton's warning. The superintendent had two heavy steel towers erected in concrete, one on each side of the tail-race of the Great Falls power house and was guying to an old cedar stump the end of a messenger cable which he had strung between the towers to carry conductors across. He and five of his men who had hold of this wire received a very severe shock and heard the electrolytic arrester about 200 feet away discharge and hold for an instant or two. As soon as the arc broke the men were relieved. On investigation it was observed that the end of the pipe to which the arrester was grounded was only five or six feet away from the men's feet, and that the earth was comparatively dry around the pipe, which was only a few inches in the ground.

This pipe was not installed for a ground, but for part of an old water main used in construction. It is quite evident that the current was seeking a better ground through the foundations of the steel towers, the concrete of which was still moist.

Mr. Thomas speaks about the bits of paper being punctured in various places. An insulator on our line was punctured in three separate places and shows the slag formed evenly around each hole.

**W. L. Waters:** I was much interested in the conclusions which Mr. Berg draws from his experiments. He finds that whenever we have an open-air arc on a circuit, we get extremely high-potential rises on the end coils of the transformers. According to his figures, we would get a potential rise equal to about 15 or 20 times normal voltage on the first 200 turns. This will probably mean that we get a potential rise of 100 to 200 times normal on the end turn of the winding, and it should be remembered that this potential rise is not a sudden strain merely, but that it continues as long as the open-air arc is on the circuit. I think that only a transformer designer can realize how serious such a potential rise would be. On large 60-cycle transformers we have up to 200 volts per turn normal potential, so if we get this sudden rise, described by Mr. Berg, it might mean 40,000 volts on the end turn of the transformer. It would not be commercially possible to insulate the transformer to stand such a high voltage between turns.

The only suggestion which Mr. Berg offers for protecting the transformer is to place a series of condensers across the various coils. There would be little difficulty in insulating the individual coils of the transformer for high voltage—the great difficulty would be in insulating the end turns of the individual coils. For these condensers to be effective, therefore, they should be connected between the various end turns of the end transformer coils, rather than across the coils themselves. I think it will be realized that the suggested remedy of putting condensers across the individual coils of the transformer would do little good, besides being unpracticable. It is well known that the weakest parts of a transformer are the various voltage taps which are brought out, and it is easily seen that the additional danger due to numerous taps being brought out from the winding to the condensers would offset any advantage which might be gained from their use. The additional cost and complication of this series of condensers would also make the size and cost of the transformer prohibitive. I think that the only practical method of protecting the transformer against these high-potential strains is the insertion of choke-coils between the transformer and line. These choke-coils will most certainly afford some protection to the windings, and it is just a question of selecting choke-coils with the required constants to give suitable protection.

I rather think, however, that Mr. Berg in his experiment has chosen conditions which are in some way different from practical operating conditions. We have been operating transformers for the past fifteen years on power circuits which are exposed frequently to open-air arcs and have done this without any extra insulation on the transformer windings and without choke-coils. According to Mr. Berg's experiment, we ought to lose our transformers every time we had an open-air arc on the circuit, and we all know that this is not the case. I think, therefore, that Mr. Berg must have had some special conditions present in his test which caused him to obtain unusual results, and that he should guard against drawing general conclusions from a limited series of special tests.

**William McClellan:** After some experience with lightning arresters at voltages varying from 11,000 to 60,000, I cannot help but think that the two methods of obtaining data as shown in the papers of this morning, while both valuable, fill very different places in the study of the subject.

So far as effectiveness is concerned, the speaker believes the method used by Mr. Creighton is of the very highest value, and it is with the greatest pleasure that he bears testimony to his enjoyment in reading the paper. It seems almost certain that the final solution of the problem will be reached by this method sooner than by any other.

It must be conceded that results obtained by a test-paper method can only be corroborative of the conclusions and predictions obtained from the experimental methods. As is well known in all laboratory work, results can only be obtained when conditions can be isolated, and most engineers will agree that in work of this kind isolation is well-nigh impossible so far as commercial lines are concerned. The variables are so many, the causes of each are so subtle, that it is difficult to get any positive knowledge of what the conditions are at the time the phenomenon occurs.

It would be well for all to note that the real problem at present in lightning protection arises in connection with transmission lines. It may safely be said that we can protect at present any kind of station, and all the future can do is to make this protection simpler and less expensive. We are far, however, from a solution of lightning protection to transmission lines. In this connection the writer can only repeat his opinion, expressed before, that the ground wire will be found eventually to be the only method which will give real protection. But the ground wire, to be adequate, will have to be installed in a more elaborate manner than is now customary. There is no doubt that in time to come we will build our transmission lines with as much care, and they will warrant as much expense, as a high-speed railroad right-of-way. I think we must recognize sooner or later that if the transmission line is to be protected adequately, so as to give practically continuous operation, we shall be compelled to put on it several times the expense that we do at present. The error we are making at present is in attempting to get line protection cheap.

**Farley Osgood:** I would ask Mr. Thomas if he can tell us from these tests something about the limits of the area of the disturbance. Not very long ago most operating engineers felt when a lightning storm came that they were likely to feel the effects of it everywhere in their system. A number of engineers now tell me that half a mile is likely to be the limit of the area disturbed. Possibly in the test made on the Taylor's Falls line this point was brought out. If I remember Mr. Vaughan's paper correctly, it indicated that one-half to three-quarters of a mile seemed to be about the limit of severe disturbances, but as an operating engineer, I feel safe in saying that we dare not have very great confidence in that statement.

I would also like to ask if any one can tell what benefits are derived from serving the phase wire near the insulator. This practice is not a general one, but some engineers follow it and they record remarkable results in the loss of a great number of insulators without the parting of the phase wire. I therefore simply bring it up as a matter for discussion.

I wish to agree with Mr. Rushmore about forming final conclusions from the results of the tests and experiments which are now going on. His reference to Mr. Thomson's chain of lightning disturbances reminds me that a year or two ago, when the sun spots were observed, and it was supposed this condition would give us a good deal of trouble, our good friends who seemed to be in pretty close touch with the folks who send us lightning storms, alarmed all the operating engineers at the prospect of some terrible lightning storms that season. These conclusions were based on very careful study, but as a matter of fact I think we had less disturbance from lightning storms that year than in any previous year.

**Dugald C. Jackson:** I wish to call attention to the enterprise and foresight of the manufacturers who have supported the experiments Mr. Creighton carried on, and likewise of the owners of transmission lines who have supported the experiments presented by Messrs. Vaughan and Neall. We have been this morning viewing the papers from the standpoint of the results that have already been attained. Now, these results are large, but they are merely indicative of the path to be followed toward a solution of the lightning difficulties. I believe that Dr. Kennelly is too much influenced by his experience in the telegraph art, when he throws out the inference that lightning protection for transmission lines will not be reasonably perfect in the future. We spend so much money for the insulation of transmission lines as compared with the insulation of telegraph lines, and the value of the apparatus to be protected is so great as compared with that in the telegraph lines, that we can afford to spend enough money to protect transmission lines and protect them thoroughly.

It used to be said that successful paralleling of alternators was impossible. Now it is one of the commonplace matters of engineering practice, this paralleling of alternators. Of course, now and then an accident occurs to paralleled alternators, but that does not alter the fact that paralleling of alternators is successful. Likewise, we seem to be in a fair way to soon see the "impossible" accomplished in the protection of transmission lines. The experiments that are now being carried on with transmission lines are doing more to bring us to a real knowledge of the characteristics of lightning strokes, and of the measures to use for protecting the lines from their injurious effects, than everything that went before. We should view the experiments that have been set forth in these papers from the standpoint of what they lead toward, and also from the standpoint of the great ingenuity and ability with which the work has been done,—not merely viewing what they show in completion. If such results and such methods of work as are laid down in Mr. Creighton's paper, or as are laid down in the paper that Messrs. Vaughan and Neall earlier presented, came from a laboratory of "pure science," these results and a statement of these methods would be heralded with acclaim. Coming from engineers, as they do, as part of the engineer's daily work, they are part of the craft of the engineer and we forget the tremendous labor and tremendous ability that have gone into the experiments, and our discussion is likely to tend toward criticism instead of encouragement. That does not seem to me to be in keeping with the pioneer character of the papers or fair to the art dealt with. A reasonable amount of acclaim given to the experimental results and beautiful methods used will encourage and lead toward the more rapid extension of such work, a result which is earnestly to be desired. The Institute is fortunate in having these papers before it for discussion, and I desire to express my particular admiration of the manner in which the authors conceived and executed their experiments and presented their results.

**Chas. P. Steinmetz:** I caution you not to accept too broadly the statement that lightning disturbances extend only over a half-mile or less. This is really not the fact. I know from my own experience that occasionally when a lightning storm passes in the Hudson valley, the lights in my house, thirty or forty miles away, go out. The statement made in the paper is correct only in that the disturbance produced by the lightning stroke, by its very abrupt discharge, extends only over a half-mile or less, possibly even over only a few poles; but internal surges produced by these lightning disturbances, as by a grounded phase resulting from the puncture of an insulator by lightning, extend over the entire system, and the latter disturbances are those which are most serious and thus most noticeable. Whereas the direct lightning stroke is only the starting point of the disturbance, the latter disturbances are really the phenomena against which we have to guard, and expect to guard, by the aluminum arrester.

With the statement made that transformers break down equally as often in the middle as at end turns, I cannot agree. It was the frequent breakdown of end turns which caused manufacturers to increase the insulation of the end turns again and again. The transformers, as they stand now, with the very heavy insulation of the end turns, may break down equally as often at the end turns as in the middle, but this merely shows that the engineering design is correct, that we have increased the insulation toward the ends so much as to give the same margin of strength throughout the entire transformer. The equal frequency of breakdown throughout the entire transformer, with the much heavier insulation of the end turns, proves that the strains are far more severe toward the ends. If we left the end turn unprotected, we would find a very disastrous state of affairs.

Regarding the weird phenomena described by Mr. Berg in his paper: it is true we can make a picture of these, as Mr Taylor shows, but what we desire Mr. Berg to give us sometime is not a mere picture—how it happened—but we expect to get equations of it.

I have seen phenomena of the same character, which are quite curious. Some years ago we built a 500,000-volt transformer—this was quite some time ago, and we knew a great deal less of very high voltages at that time than now. With the transformer fully assembled, and with the terminals brought out from the oil, we were never able to run the transformer up to full voltage. It always broke down. If we took the terminals off, below the point where they come out of the oil, leaving the transformer connected with full voltage, we could run the voltage considerably beyond 500,000, without doing any damage. It was merely a case of a small terminal capacity, and by bringing the terminals out in the air, the brush discharge produced a high-frequency oscillation, which made the transformer break down internally, at a nominal effective voltage below that which it would stand as a steady stress.

**E. E. F. Creighton:** In reply to Mr. Lincoln's question, of whether there was dynamic current on when these records, Figs. 3, 4, and 5, were taken, I will say there was not. Of course, if there had been dynamic current there, the arc would have continued to play and the record would have been lost. The record shows nothing but the oscillations of the circuit.

In regard to the overhead grounded wires, I think that phase of the subject has been discussed pretty thoroughly. The overhead grounded wire cannot produce complete protection, but it will, as a rule, bring the protection within the range of the insulation of the line, and in that way reduce the probability of interruptions to a very small value. When a very heavy direct discharge strikes the overhead wire, there is still a possibility that the line will arc to ground, due to "side-stroking." The farther away the ground wires are from the line wires, the less will be the danger from this source.

A number of years ago we made some laboratory experiments on the protection afforded by the overhead ground wire, and we found that the wire gave about fifty per cent. less sparking potential with the overhead grounded wire placed above it. The test was carried out by placing a large plate of sheet metal above the wires experimented upon, and regarding the plate as the cloud.

In regard to the storms themselves, there is no doubt that every storm varies in its characteristics from every other storm, to a certain extent. We might get an analogy by noting that in any dusty place, around a building or fence corner, every wind current or every wind storm that comes up has a different effect; but if you watch you will find that little currents or whirls of air will frequently form at certain places. You find the same thing with cloud effects. Out on the plains thunder clouds may appear anywhere. In the mountains the heated air in the canyons will cause thunder clouds to form repeatedly in the same location, and the mountains themselves give a direction to the winds. Although I think the direct observation of storms in general gives very little practical information in engineering, yet an attempt at classification explains some differences in their destructive effects. Not very long ago we observed a storm which was rather peculiar. It was made up of clouds in the form of an inverted cone. I was stationed at a point about two miles away from the apex of the cone, and I observed that the lightning strokes would start from all directions in the body of the cloud-cone and discharge at one particular point, the apex. The conditions are shown in the figure.

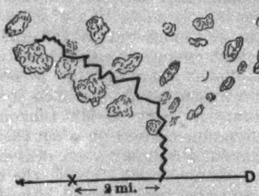

FIG. 1

At the station where the speaker was there was not even rain until some time after the lightning display ceased. The electrical storm was severe but its effect on the transmission line was negligible. There were over fifty strokes at the apex of the clouds. If the apex of the clouds had been situated directly over the station or line the destructive effects would have been great, and the protective apparatus would have been called on for its maximum discharge rate.

The distance to the point on the earth struck by the discharge was located by the well-known method of counting seconds between the instants of seeing the flash and hearing the thunder, and allowing five seconds to the mile. Since the apex of the cloud was only ten seconds distant and the thunder would roll for fifteen seconds after it started, some confusion would naturally be experienced unless the conditions were analyzed. There were at least three definite relations between the thunder and lightning which a fortunate situation relative to the storm aided in checking.

1. There was the flash to ground, followed about four seconds afterward by mild rolling thunder, which increased in intensity up to ten seconds, and then ended in a loud crash. This thunder was due to a discharge which started in the clouds directly overhead at an elevation of nearly a mile and darted to the apex, gathering a greater quantity of electricity as it went. This increase in the quantity of electricity is not the only factor affecting the noise of the thunder. The wet atmosphere in the clouds relative to the dry atmosphere between cloud and earth was a good conductor. There would therefore be less tendency for the discharge in the cloud to collect in one streak. Between these two effects, the noise of the rolling thunder increased despite the fact that it came to me from a greater distance.

2. After an interval of ten seconds following the flash to earth the thunder started with a heavy crash, and then rolled during eight to fifteen seconds, gradually diminishing in intensity. This thunder was due to a stroke coming from the farther side of the cone to the apex.

3. After the flash to earth there was an interval of ten seconds and then a crash of thunder with little or no rolling. This thunder was due to a stroke moving through the clouds to the apex at right angles to the point of observation. All the path of discharge being at nearly the same distance the sound from the different portions arrived at the same time, hence the lack of rolling.

Since the strokes occurred at intermediate angles also, these three effects were obtained only to a lesser degree.

The theory of the formation of thunder clouds leads to the conclusion that this conical form of storm cloud occurs frequently on the line.

Mr. Taylor questions the use of the word lightning to express all abnormal conditions of potential on the line. That name is due to Dr. Steinmetz—it was a very convenient term, and we adopted it. Subsequently, the use of the word "lightning" was discussed by several interested engineers, with the result that Dr. Steinmetz and the writer agreed to use the term lightning only in its time-honored sense—cloud discharges and their induced effects. Some general term is needed to cover the various abnormal surges which occur on a transmission line. Several words were discussed but none agreed upon.

Mr. Taylor brings up the question of lightning frequency. I think my statements will be clear if one accepts the general term lightning as any abnormal condition of tension on the line. A frequency of one million cycles per second was measured by a number of coils, described in the paper, and I am very glad to get the opinion of wireless-telegraph engineers that they also have noticed frequencies of that order, measured by a different method. Dr. Steinmetz has made calculations on the probable frequency of cloud discharges, and the value has come out of the order of a million cycles. A cloud discharge may have a frequency of only fifty thousand, or it may have no frequency at all—may be a non-oscillatory discharge. There is reason to believe that this latter condition may obtain under some circumstances. The lightning is gathering from perhaps miles around, or may be merely passing through a few acres of cloud, but in gathering it has to pass through a high resistance—pass from point to point in the clouds, in the form of brush discharge. Therefore, it seems reasonable to assume that certain lightning strokes can occur without any oscillations at all.

Mr. Taylor brings up the question of the resistance of the earth independent of the contacts. The usual contact resistance of an ordinary pipe earth, if well made, will be about fifteen ohms. It may be considered that the resistance is concentrated in the immediate neighborhood of the pipe. In the case referred to, the data is given for a condition out in the Rocky Mountains, where as the term indicates, everything is rocky—the mountains are composed of solid rocks. The rock is dry, hard, and of low conductivity. The conducting earth between the two points measured was in a very narrow canyon, consequently the resistance depended upon the distance. In another case the earth resistance was very much less, being only a few ohms. In a neighborhood where there is plenty of good loamy soil, and plenty of moisture, there is no doubt that the actual earth resistance, independent of the local and contact resistances, would be very small.

In regard to the questions brought up in connection with Mr. Berg's paper, I wish to corroborate the statement made by Mr. Berg, that the biggest problem we have to-day is not the protection against cloud lightning, but protection against the internal surges. Some of the worst conditions observed last summer in Colorado were due to these internal surges, combined with short-circuits. This combination gives the worst condition that can exist on the line, outside of a direct stroke. A direct stroke affects only a small locality, whereas a grounded phase, combined with a short-circuit, may affect the whole circuit, and usually does.

There is just one other point I wish to take up: the conditions of further study. Personally, I am indebted to a number of operating engineers who have assisted in this work; and the operating engineer has put up to him part of the problem which he must solve himself. So far as we are able to do so, we shall continue to study; but from the factory end we cannot hope to solve the entire problem, because the conditions on one line are not the same as on another. The problem relates to protection against accidentally grounded phases, the installation of the number of lightning arresters necessary to effect this protection, and the spark potential of the lightning arrester.

Now, in order to make a lightning arrester that is marketable, it is essential to keep the price down to a value which is comparable to the cost of the apparatus to be protected—say the transformer, the generator, or whatever it may be. This condition has necessitated the use of a gap in series with an aluminum arrester. The questions are: what gap-setting to use and how many of these aluminum arresters must be placed on a transmission system; that is, how many stations must be protected with the aluminum arrester, to give protection to all the rest? For example, if we have thirty stations, will the protection of ten of them with aluminum arresters protect the balance against internal surges?

**E. J. Berg:** I have purposely refrained from giving any theory for the action of these arcing grounds, because an incomplete theory is worse than no theory at all. I believe, however, that Mr. Taylor's theory will not apply. Referring to the diagrams showing grounding of one side of the open delta, you see that the transformer nearest to ground is subjected to a voltage which corresponds to 3.25 inches striking distance. At that time the striking distance across the outside transformer is 3.21 inches. If Mr. Taylor's theory were correct, the striking distance across this latter transformer would have been 2 inches.

It may be of interest to add that at the time of such an arcing ground not only are the end turns subjected to high voltages, but also to considerably greater current, and correspondingly greater heating, than the other turns.

Regarding Mr. Waters' discussion: I tried, as you see from the paper, to overcome the difficulties discussed in the paper, by the use of reactive coils, but was unable to reduce materially the stresses incidental to these arcing grounds. This was true even when using a large number of coils, the turns of which were approximately one-sixth of the total number of turns in the transformer. These coils did not contain any iron, but they were of the same dimensions as the transformer coils.

Regarding the stresses on the end turns, Mr. Waters is no doubt perfectly right, but it may interest you to know that the company with which I am connected insulates the end turns of its high-potential transformers for one hundred to two hundred times the normal voltage. For very high-voltage transmission, it is likely that delta-delta connection will not be used, but instead the delta-Y grounded neutral, with which an arcing ground can not occur since such a ground means a short-circuit, and consequently the line has to be cut out of service.

**Percy H. Thomas:** I wish first to say a word about Mr. Berg's paper. I think it is very important here to draw a distinction in arcs, so-called. The arc which carries a great deal of current, and in which there is no cooling of the arc between alternations, and the type of arc that is under discussion, in which apparently there is a practical healing of the gap between alternations, are entirely different things. I think it is clear that these rises of potential are produced by that type of arc which drops out between alternations; in other words, it is but little more than a constant repetition of the condition of the initial ground. It is pretty well known that when a transmission wire grounds, the charge from the capacity to ground starts oscillations in the system and produces waves and reflections of the same which may cause a rise of potential. This may have in the simple case a value twice normal, or in more complex cases somewhat more than this, on account of the presence of series inductance and on account of variations of line capacity, etc.; but the action does not give enormous voltages, and introduces no new principles or features. I think this point of view will explain a great many of the phenomena reported in Mr. Berg's paper. I do not find here anything new, in the way of a danger which we have not heretofore recognized. By any one who is familiar with experimental work of that character, the difference in the types of these arcs is easily detected. There is a rough, irregular sound in all arcs where there is a large percentage of "healing" in the gaps between alternations.

Another thing, which has tended to increase the apparent rise of potential reported in Mr. Berg's paper, is the fact that he has given jumping distances, and not voltages. This causes a considerable exaggeration with voltages higher than 25,000.

I also wish to make one or two comments on Mr. Creighton's paper. I was going to raise the same point as was raised by Mr. Taylor in connection with the production of a lightning frequency of 3,000 alternations. I see the explanation of this low frequency is that the term " lightning " does not indicate cloud lightning, but the natural discharge of the line. I want to protest against this use of this word "lightning." I do not think there is anything that will cause us more confusion than to use the term generally for all sorts of discharges in the circuit and also for all disturbances outside, as well as the natural lightning phenomena. If we could all get together and agree that we would give the word " lightning " a certain new meaning it would perhaps not be misunderstood. but we are writing for a great many people over whom we have no control and they will not understand it at all.

Another point: In regard to the word " static ", I wish to defend Mr. Berg. If there is one term that we need in the business, in electrical high-tension work, it is a general term to describe these disturbances which come from discharges or surges in the line, due to other than normally generated electromotive force. These disturbances are entirely different in their nature from the so-called dynamic electricity. I know of no word anywhere which nearly so well expresses the idea as the word " static."

**Chas. P. Steinmetz:** Lightning.

**Percy H. Thomas:** The word " static " is used broadly at the present time with this significance. It is true, surges are not *static* electricity, but this seems to me a meaningless objection. I wish strongly to urge the general adoption of this term. No one will be misled, and it fills a long-felt want.

I wish to inquire of Professor Creighton, whether the use of salt, in perfecting ground connections using iron, would not be a pretty dangerous recommendation, on account of the corrosion. It is well enough for experimental purposes, to determine losses, but it seems to me would be undesirable for use in permanent grounds.

I wish to state that in the past I have been inclined to doubt the efficiency of overhead ground wires and their effectiveness, but at the present time I am pretty well convinced that ground wires give the best and almost the only hope of completely protecting transmission lines against lightning. The point I attempted to make in my paper, and which seems to have been taken too broadly, is that the particular experiments referred to in the paper have not proved that these particular ground wires were effective. If these ground wires are properly installed, I believe they offer a very promising remedy. The danger is, first, that as they are ordinarily used, ground wires are not sufficiently separated from the transmission wires, and lightning striking them will also jump to the wire itself; and second, that they are not so located that the lightning will always strike them first. There is always a probability that there is one transmission wire, or possibly two, which is at a lower potential with regard to the cloud than the ground wire itself. There will be a tendency for a discharge to pick out this transmission wire rather than the ground wire.

I cannot agree with Dr. Steinmetz that it is not possible to distinguish between the effect of a bound charge and a direct stroke of lightning. To my mind, this difference is vital, for the reason that the character of protection required will be different for the two types of disturbances. If it is a matter of a bound charge, you must have a static shield, which is difficult to obtain completely, but the intercepting of a direct stroke may not be so difficult. There can be no doubt that all these types of disturbances do affect the line, whether it is a bound charge, direct stroke or electromagnetic induction. The vital question is, which sort is it that punctures insulators and splits the pole? If we find which one of them does that real harm, we can then protect against that, and let the others go.

Mr. Vaughan's paper shows that there are a tremendous number of lightning disturbances which do not go over the insulators. I think a careful study of the paper proves that the attack which did the damage came from the air.

Mr. Osgood asks about the extent of the disturbances shown by the Taylor's Falls tests. There are two criteria: first, the individual stroke, which I believe is felt in severe form on only a very few poles; and second, the static waves in the line which are of limited energy and voltage but which travel all over the system. The evidence in Mr. Vaughan's paper and other evidence corroborate this.

I wish to protest against the statement that we find about three or four times on every occasion when we have a lightning-arrester paper, that this sort of data which is presented should not be taken seriously, that it will not do to infer too much from it, that we must reserve our judgment, that it is necessary to prove these things before people can accept them, etc. It seems to me that is a narrow view to take of the subject. If all had taken that view, we would know almost nothing about lightning at the present time. One or two examples from other branches of scientific work may be called to mind to show how untrue such a position is. Take the investigations of Hertz, who drew inferences from ordinary microscopic sparks in an exploring coil—the theory he built up has proved itself to be true. Our data are fully as illustrative. Take the case of radioactivity, the results that have been obtained from the study of very minute and apparently most insignificant measurements. Similar is the work of J. J. Thomson and others on the ionization of gases. All these results were worked out from data naturally much more inconclusive than the data we have on lightning experiments.

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# THREE-PHASE POWER-FACTOR

BY AUSTIN BURT

Based on the commonly accepted definition of power-factor, as " The ratio of true power to volt-amperes ", there can be no single factor that will exactly express such a physical relationship in a delta-connected, unsymmetrical, three-phase system.

It is possible, however, to determine, by practical methods, the weighted mean of the three power-factors of the single-phase paths of such a three-phase system, and to express that value by a single-factor. It has been suggested that such a factor might have importance under certain commercial conditions.

It is the purpose of this paper, first, to derive from the various relations that exist between the electromotive forces and currents in a three-phase, delta-connected system, a general expression which will enable the mean power-factor to be determined exactly; and, secondly, to develop a method by which the required values employed in the above expression may be readily determined from the standard switchboard instruments.

It is proposed, therefore, to find an expression for the total energy volt-amperes and for the total volt-amperes in the general case of a three-phase system in which the electromotive forces and currents in the single-phase paths may have any assigned value and phase relation. The ratio of these two expressions will be the desired mean power-factor. The total volt-amperes will be taken as derived from the total wattless volt-amperes and the total energy volt-amperes, or, in other words, from the sum of the wattless volt-amperes and from the sum of the energy volt-amperes existing in each single-phase path.

In the simple case of a single-phase system let

$E$ = the impressed electromotive force
$I$ = the current in the circuit resulting from inductive conditions in the receiver
$\phi$ = time-angle between $E$ and $I$.

Fig. 1 will represent vectorially such a single-phase system. Then if the energy volt-amperes be represented by $P$, and wattless volt-amperes by $P_w$, we have,

$$P = I \cos \phi \, E \tag{1}$$

$$P_w = I \sin \phi \, E \tag{2}$$

From the definition of power-factor we have,

$$\text{power-factor} = \frac{P}{I\,E} = \frac{I \cos \phi \, E}{I\,E} = \cos \phi \tag{3}$$

and,

$$\phi = \cos^{-1} \text{ (power-factor)} \tag{4}$$

from (1) and (2)

$$I\,E = \frac{P}{\cos \phi} = \frac{P_w}{\sin \phi} \tag{5}$$

and by multiplication,

$$\frac{\sin \phi}{\cos \phi} = \frac{P_w}{P} = \tan \phi \tag{6}$$

then from (6) and (4),

$$\phi = \tan^{-1} \left( \frac{P_w}{P} \right) = \cos^{-1} \text{ (power-factor)} \tag{7}$$

It is seen, therefore, that the angle $\phi$, whose tangent is the ratio of the wattless ampere-volts to the energy ampere-volts, will give directly the power-factor from its cosine. A general expression for the total wattless ampere-volts and the total energy ampere-volts in a three-phase system, gives a ratio whose value is a weighted mean of the similar ratios of the several single-phase paths, and the angle whose tangent is this mean ratio gives the mean power-factor desired from its cosine.

In the three-phase system under consideration the total wattless ampere-volts is the algebraic sum of the wattless ampere-volts, and the total energy ampere-volts is the sum of the energy ampere-volts in each of the three single-phase paths of the system.

Such a three-phase system is represented by the vector diagram in Fig. 2. Let the impressed electromotive forces and currents in the single-phase windings be represented respectively by $E_{ab}$, $E_{bc}$. $E_{ca}$, and $i_a$, $i_b$, $i_c$, and the phase relations between the several electromotive forces and currents by $\alpha'$, $\beta'$, $\gamma'$, with the additional convention that angles measured counter clockwise are lagging, and measured clockwise they are leading.

In Fig. 2, then, the delta $(a\,b\,c)$ represents the value and phase relation between any selected values of $E_{ab}$, $E_{bc}$, and $E_{ca}$. The current in phase $a\,b$ and its phase relation to $E_{ab}$ is represented by vector $i_a$ at angle $\alpha'$ with $E_{ab}$. Similarly the currents in phases $b\,c$ and $c\,a$ are represented by vectors $i_b$ at $b$ and $i_c$ at $c$, making lag-angles $\beta'$ and $\gamma'$ respectively with $E_{bc}$ and $E_{ca}$. It should be remarked that angles $\alpha'$, $\beta'$ and $\gamma'$ could just as well have been taken leading as lagging.

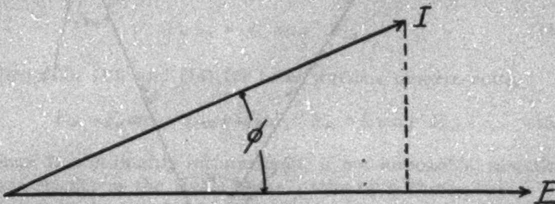

FIG. 1

The star or line current will be the resultant of the currents in any two adjacent paths; that is, the current at $a$ will be the resultant of the single-phase current in $c\,a$, or $i_c$, and the current in $a\,b$, or $-i_a$.

$i_c$ is represented at $a$ by the broken vector $a\,a''$, and $-i_a$ by vector $a\,a'$. The resultant of these two vectors, $I_a$, therefore represents, in length and position, the line current at $a$. Similarly, the line current at $b$ is the resultant of $i_a$ and $-i_b$, which are represented at $b$ by $b\,b''$ and $b\,b'$ respectively. Therefore, vector $I_b$ represents, in length and position, the line current at $b$. And again, at $c$, the vector $I_c$ is the resultant of $i_b$ and $-i_c$, represented by the vectors $c\,c''$ and $c\,c'$, and it therefore represents the line current at $C$.

This diagram therefore illustrates graphically the essential elements, in general, of any delta-connected, three-phase system.

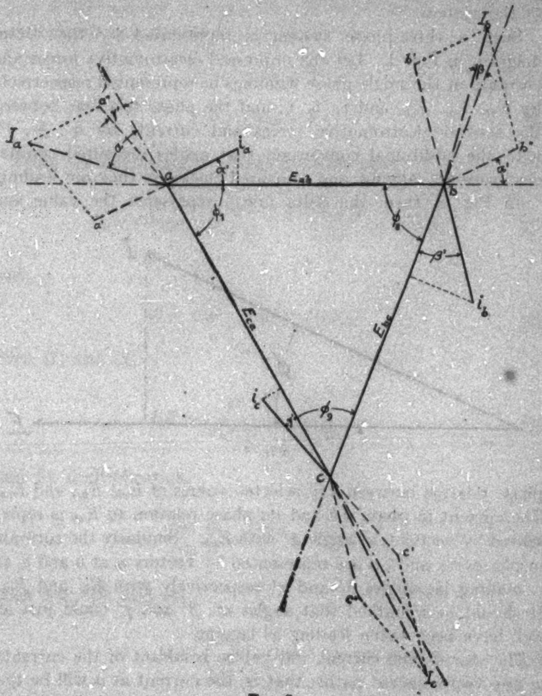
$I_a$
$a''$
$\gamma'$
$\alpha$
$i_a$
$\alpha'$
$a$
$E_{ab}$
$b$
$I_b$
$b'$
$\beta$
$b''$
$\alpha'$
$a'$
$\phi_1$
$\phi_2$
$\beta'$
$i_b$
$E_{ca}$
$E_{bc}$
$i_c$
$\gamma'$
$\phi_3$
$c$
$c'$
$c''$
$I_c$

FIG. 2

The energy ampere-volts in phase $a\,b$, in phase $b\,c$, and in phase $c\,a$ are then, if $P_{ab}$, $P_{bc}$, and $P_{ca}$ represent the respective single-phase paths,

$$P_{ab} = i_a \cos \alpha, E_{ab} \tag{8}$$

$$P_{bc} = i_b \cos \beta' E_{bc} \tag{9}$$

$$P_{ca} = i_c \cos \gamma' E_{ca} \tag{10}$$

adding (8), (9) and (10) for total energy ampere-volts,

$$P = i_a \cos \alpha' E_{ab} + i_b \cos \beta' E_{bc} + i_c \cos \gamma' E_{ca} \tag{11}$$

Similarly the wattless ampere-volts, if $(P_w)_{ab}$, $(P_w)_{bc}$ and $(P_w)_{ca}$ represent the respective single-phase paths, are,

$$(P_w)_{ab} = i_a \sin \alpha' E_{ab} \tag{12}$$

$$(P_w)_{bc} = i_b \sin \beta' E_{bc} \tag{13}$$

$$(P_w)_{ca} = i_c \sin \gamma' E_{ca} \tag{14}$$

adding (12), (13) and (14) for total wattless ampere-volts,

$$P_w = i_a \sin \alpha' E_{ab} + i_b \sin \beta' E_{bc} + i_c \sin \gamma' E_{ca} \tag{15}$$

Since it is ordinarily inconvenient, if not impossible, to make measurements in the single-phase paths of a three-phase system it is required to find more useful expressions than (11) and (15). General expressions, based on and equal to (11) and (15), with external values for electromotive forces and currents, may be derived by a consideration of the relations existing in vector diagram, Fig. 3. This diagram is in all essential particulars an exact duplicate of Fig. 2. It is desired to prove from it that the following general proposition is true: that for any selected position of point $O$ whatsoever, with lines $O\,e$, $O\,f$ and $O\,g$ passing through the delta vertices $a$, $b$, and $c$, respectively, the sum of the products of the projection $a\,e$, of line-current vector $I_a$ on $O\,e$, by $O\,a$, and the projection $b\,f$, of line current $I_b$ on $O\,f$, by $O\,b$, and the projection $c\,g$, of line-current vector $I_c$ on $O\,g$, by $O\,c$ is equal to $P$ the total energy volt-amperes and therefore equal to and may be substituted for equation (11).

Similarly, it is desired to prove that the sum of the products of $e\,a''$ by $O\,a$, and $f\,b''$ by $O\,b$ and $g\,c''$ by $O\,c$ is equal to $P_w$ the total wattless volt-amperes, and therefore equal to and may be substituted for equation (15).

Expressing these statements in form it is desired to prove that,

$$P \quad = I_a \cos \alpha'' \, O\,a + I_b \cos \beta'' \, O\,b + I_c \cos \gamma'' \, O\,c \qquad (16)$$

$$P_w = I_a \sin \alpha'' \, O\,a + I_b \sin \beta'' \, O\,b + I_c \sin \gamma'' \, O\,c \qquad (17)$$

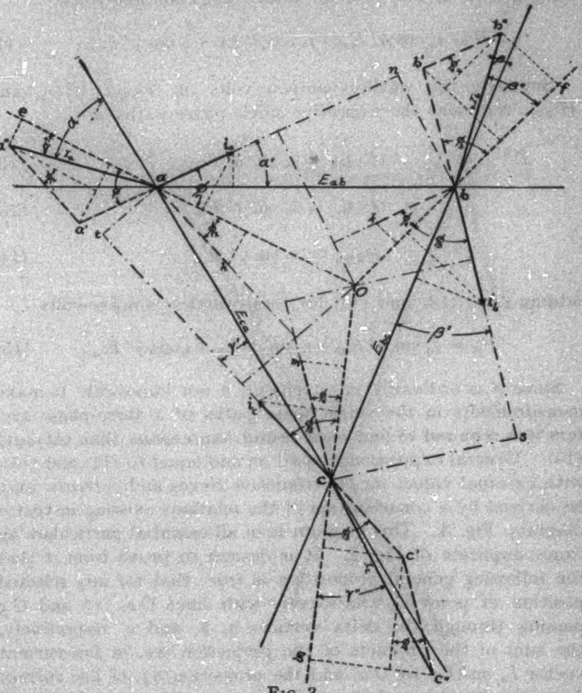

FIG. 3

Referring, successively, to the following pairs of triangles, $a\,O\,b$ and $a\,n\,b$, $b\,O\,c$ and $b\,s\,c$, $c\,O\,a$ and $c\,t\,a$, and noting that $b\,k$ is equal to and parallel with vector $i_a$, that $c\,m$ is equal to and parallel with vector $i_b$, and, finally, that $a\,h$ is equal to and parallel with vector $i_c$, we have the following set of equations:

$$i_a\, E_{ab} \cos \alpha' = i_a\, O\, a \cos \phi_1 + i_a\, O\, b \cos \phi_4 \qquad (18)$$

$$i_b\, E_{bc} \cos \beta' = i_b\, O\, b \cos \phi_3 + i_b\, O\, c \cos \phi_6 \qquad (19)$$

$$i_c\, E_{ca} \cos \gamma' = i_c\, O\, c \cos \phi_5 + i_c\, O\, a \cos \phi_2 \qquad (20)$$

$$i_a\, E_{ab} \sin \alpha' = i_a\, O\, a \sin \phi_1 - i_a\, O\, b \sin \phi_4 \qquad (21)$$

$$i_b\, E_{bc} \sin \beta' = i_b\, O\, b \sin \phi_3 + i_b\, O\, c \sin \phi_6 \qquad (22)$$

$$i_c\, E_{ca} \sin \gamma' = i_c\, O\, c \sin \phi_5 - i_c\, O\, a \sin \phi_2 \qquad (23)$$

adding (18), (19), and (20) and referring to (11), we have,

$$\begin{aligned} i_a \cos \alpha'\, E_{ab} + i_b \cos \beta'\, E_{bc} + i_c \cos \gamma'\, E_{ca} = P = \\ (i_a \cos \phi_1 + i_c \cos \phi_2)\, O\, a + (i_b \cos \phi_3 + i_a \cos \phi_4)\, O\, b + \\ (i_c \cos \phi_5 + i_b \cos \phi_6)\, O\, c \qquad (24) \end{aligned}$$

but from Fig. 3, by inspection,

$$\begin{aligned} (i_a \cos \phi_1 + i_c \cos \phi_2)\, O\, a = (a\, a' \cos \phi_1 + a'\, a'' \cos \phi_2)\, O\, a = a\, e. \\ O\, a = I_a \cos \alpha''\, O\, a \qquad (25) \end{aligned}$$

and

$$\begin{aligned} (i_b \cos \phi_3 + i_a \cos \phi_4)\, O\, b = (b\, b' \cos \phi_3 + b'\, b'' \cos \phi_4)\, O\, b = b\, f. \\ O\, b = I_b \cos \beta''\, O\, b \qquad (26) \end{aligned}$$

and

$$\begin{aligned} (i_c \cos \phi_5 + i_b \cos \phi_6)\, O\, c = (c\, c' \cos \phi_5 + c'\, c'' \cos \phi_6)\, O\, c = c\, g. \\ O\, c = I_c \cos \gamma''\, O\, c \qquad (27) \end{aligned}$$

substituting these results in (24) we have,

$$P = I_a \cos \alpha''\, O\, a + I_b \cos \beta''\, O\, b + I_c \cos \gamma''\, O\, c \qquad (28)$$

thus proving equation (16).

Similarly adding (21), (22), and (23), there are, referring also to (15),

$$i_a \sin \alpha' \, E_{ab} + i_b \sin \beta' \, E_{bc} + i_c \sin \gamma' \, E_{ca} = P_w =$$
$$(i_a \sin \phi_1 - i_c \sin \phi_2) \, O\,a + (i_b \sin \phi_3 - i_a \sin \phi_4) \, O\,b +$$
$$(i_c \sin \phi_5 + i_b \sin \phi_6) \, O\,c \tag{29}$$

but from Fig. 3 by inspection,

$$(i_a \sin \phi_1 - i_c \sin \phi_2) \, O\,a = (a\,a' \sin \phi_1 - a'\,a'' \sin \phi_2) \, O\,a = e\,a''.$$
$$O\,a = I_a \sin \alpha'' \, O\,a \tag{30}$$

and

$$(i_b \sin \phi_3 - i_a \sin \phi_4) \, O\,b = (b\,b' \sin \phi_3 - b'\,b'' \sin \phi_4) \, O\,b = f\,b''.$$
$$O\,b = I_b \sin \beta'' \, O\,b \tag{31}$$

and

$$(i_c \sin \phi_5 + i_b \sin \phi_6) \, O\,c = (c\,c' \sin \phi_5 + c'\,c'' \sin \phi_6) \, O\,c = g\,c''.$$
$$O\,c = I_c \sin \gamma'' \, O\,c \tag{32}$$

substituting these results in (29) we have,

$$P_w = I_a \sin \alpha'' \, O\,a + I_b \sin \beta'' \, O\,b + I_c \sin \gamma'' \, O\,c \tag{33}$$

thus proving equation (17).

Equations (28) and (33) are general expressions for any possible location of point $O$. If, therefore, point $O$ be taken at vertex $c$ in Fig. 3 there are.

$$\alpha'' = \alpha \qquad O\,a = E_{ca}$$
$$\beta'' = \beta \qquad O\,b = E_{bc}$$
$$O\,c = 0.$$

substituting these values in (28) and (33) there are:

$$P = I_a \cos \alpha \, E_{ca} + I_b \cos \beta \, E_{bc} \tag{34}$$

$$P_w = I_a \sin \alpha \, E_{ca} + I_b \sin \beta \, E_{bc} \tag{35}$$

Let

$$P_{ca} = I_a \cos \alpha \, E_{ca} \tag{36}$$

$$P_{bc} = I_b \cos \beta \, E_{bc} \tag{37}$$

then from (34),

$$P = P_{ca} + P_{bc} \tag{38}$$

A standard three-phase wattmeter, consisting essentially of two single-phase measuring elements, if placed in the system represented by Fig. 2, with the current coil of one element in line current represented by vector $I_a$ and electromotive force coil across phase $c\,a$, and with the current coil of the second element in line current represented by vector $I_b$ and electromotive force coil across phase $b\,c$, will measure by the first element that portion of total power, $P$, expressed by $P_{ca}$, and by the second element that portion expressed by $P_{bc}$, the two combined giving the total energy ampere-volts, $P$.

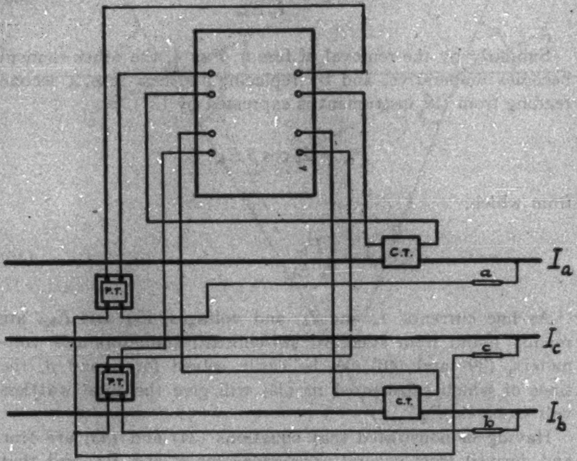

Fig. 4

It will be observed by a comparison of (34) and (35), that $P_w$ may be derived from $P$ by substituting the sines of $\alpha$ and $\beta$ for the cosines, and further it will be observed, that $\alpha$ and $\beta$ may be obtained from (36) and (37) provided the single-phase elements of the three-phase wattmeter could be read separately.

A method for accomplishing this result consists in causing to become inoperative, first one element and then the other, by opening the potential circuit of the element. Fig. 4 shows a standard connection of a three-phase switchboard wattmeter operated by current and potential transformers. At $a$ $b$ and $c$

are shown the usual primary fuses for the potential transformer. $I_a$, $I_b$ and $I_c$ are the line currents. By removing fuse $b$ the wattmeter element operated by current $I_b$ and electromotive force across $b\,c$ becomes inoperative and a reading taken from the instrument is expressed by (36) or,

$$P_{ca} = I_a \cos \alpha \, E_{ca}$$

from which,

$$\operatorname{Cos} \alpha = \frac{P_{ca}}{I_a \, E_{ca}} \qquad (39)$$

Similarly by the removal of fuse $a$, Fig. 4, the other element becomes inoperative, and by replacing the first fuse, a second reading from the instrument is expressed by (37), or

$$P_{bc} = I_b \cos \beta \, E_{bc}$$

from which,

$$\operatorname{Cos} \beta = \frac{P_{bc}}{I_b \, E_{bc}} \qquad (40)$$

As line currents, $I_a$ and $I_b$, and voltages, $E_{ca}$ and $E_{bc}$, are readily found from standard switchboard ammeters and voltmeters, (39) and (40) can be easily solved for $\alpha$ and $\beta$, the sines of which substituted in (35) will give the total wattless volt-amperes, $P_w$.

Having demonstrated that equations (34) and (35) are true and derived from general expressions for $P$ and $P_w$, and that they may be solved practically, it follows that values determined by them when substituted in equation (7) will give the desired value for $\phi$ and thus also the proposed mean power-factor.

It may be of interest to take the simple case of a single-phase load in the three-phase system under consideration, and derive the power-factor by this method.

The same values may be assumed as represented by Fig. 2, with the single-phase inductive load in phase $a\,b$, and represented by $i_a$. Currents $i_b$ and $i_c$ will be absent from phases $b\,c$ and $c\,a$, and therefore equal to zero.

This condition of affairs is represented more plainly by Fig. 5, in which,

$$\begin{array}{lll} I_a = i_a & \phi_1 = \alpha = \alpha' + \phi_7 & O\,a = E_{ca} \\ I_b = i_a & \phi_4 = \beta = \phi_8 - \alpha' & O\,b = E_{bc} \\ I_c = 0 & & O\,c = 0 \end{array}$$

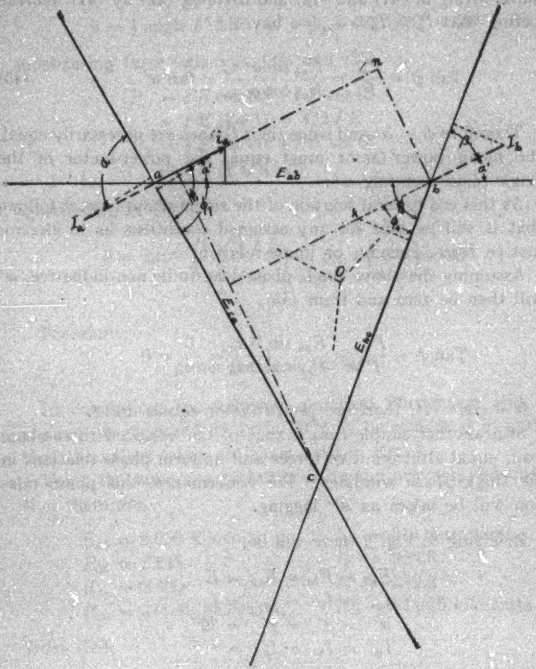
n
$i_a$
$\alpha$
$\alpha'$
a
$E_{ab}$
$\phi_1$
$\phi_7$
$I_a$
$\beta$
$I_b$
$\alpha'$
b
$\phi_8$
k
$\phi_4$
O
$E_{ca}$
$E_{bc}$
c

FIG. 5

substituting these values in equation (24), and (29)

$$P = I_a \cos(\alpha' + \phi_7)\, E_{ca} + I_b \cos(\phi_8 - \alpha')\, E_{bc} \tag{41}$$

$$P_w = I_a \sin(\alpha' + \phi_7)\, E_{ca} - I_b \sin(\phi_8 - \alpha')\, E_{bc} \tag{42}$$

But it is seen from Fig. 5 that,

$$E_{ca} \cos (\alpha' + \phi_7) + E_{bc} \cos (\phi_8 - \alpha') = E_{ab} \cos \alpha' \qquad (43)$$

$$E_{ca} \sin (\alpha' + \phi_7) - E_{bc} \sin (\phi_8 - \alpha') = E_{ab} \sin \alpha' \qquad (44)$$

substituting in (41) and (42) and dividing (42) by (41), remembering that $I_a = I_b = i_a$, we have,

$$\text{Tan}\ \phi = \frac{P_w}{P} = \frac{E_{ab} \sin \alpha' \, i_a}{E_{ab} \cos \alpha' \, i_a} = \tan \alpha' \qquad (45)$$

Therefore $\phi = \alpha'$ and since their cosines are necessarily equal, the mean power-factor must equal the power-factor of the single-phase winding $a\,b$.

As this is a general solution of the single-phase case, it follows that it will be true for any assigned conditions as to electromotive force, current, or phase-relation.

Assuming the above single-phase load to be non-inductive, $\alpha'$ will then be zero and from (45),

$$\text{Tan}\ \phi = \frac{P_w}{P} = \frac{E_{ab} \sin 0 \, i_a}{E_{ab} \cos 0 \, i_a} = \frac{0}{1} = 0$$

$0 = \cos^{-1} (1)$, therefore power-factor equals unity.

Still another simple case is that of the balanced three-phase load, equal electromotive forces and uniform phase-relations in the single-phase windings. For convenience, this phase relation will be taken as 30° lagging.

Referring to Fig. 2 there will be,

$$\begin{aligned} E_{ab} &= E_{bc} = E_{ca} = E \\ i_a &= i_b = i_c = i \\ \alpha' &= \beta' = \gamma' = 30^\circ \\ I_a &= I_b = I_c = I \end{aligned}$$

By inspection from Fig. 2,

$$\phi_7 = \phi_8 = \phi_9 = 60^\circ$$

and

$$\begin{aligned} \text{angle}\ a'\,a\,a'' &= \phi_7 + \alpha' - \gamma \\ &= 60^\circ + 30^\circ - 30^\circ = 60^\circ \end{aligned}$$

therefore, since $a\,a' = a\,a'' = i$, there is

$$\alpha = \tfrac{1}{2}\text{ angle } a'\,a\,a'' + \gamma' = 30^\circ + 30^\circ = 60^\circ$$

and also,

$$\begin{aligned}\text{angle } b'\,b\,b'' &= \phi_s + \beta' - \alpha' \\ &= 60^\circ + 30^\circ - 30^\circ = 60^\circ\end{aligned}$$

therefore, since $b\,b' = b\,b'' = i$, there is

$$\beta = \tfrac{1}{2}\text{ angle } b'\,b\,b'' + \alpha' - \phi_s = 30^\circ + 30^\circ - 60^\circ = 0^\circ$$

substituting these values in (34) and (35),

$$\begin{aligned}P &= I\,E\cos 60^\circ + I\,E\cos 0^\circ \\ &= I\,E\,(\tfrac{1}{2}+1) = 3/2\,I\,E \\ P_w &= I\,E\sin 60^\circ + I\,E\sin 0^\circ \\ &= I\,E\,(\tfrac{1}{2}\sqrt{3}+0)\end{aligned}$$

substituting in (7),

$$\phi = \tan^{-1}\left(\frac{\tfrac{1}{2}\sqrt{3}\,I\,E}{\frac{3}{2}\,I\,E}\right) = \tan^{-1}\left(\frac{1}{\sqrt{3}}\right) = 30^\circ$$

Therefore,

$$\text{power-factor} = \cos 30^\circ$$

In conclusion, the following practical illustration will emphasize the proposed method. It may be remarked in passing that the values taken are those used in Fig. 2.

Using the same nomenclature as in the previous demonstration there are,--

| | |
|---|---|
| $E_{ab} = 2.050$ kilovolts. | $I_a = 214.8$ amperes. |
| $E_{bc} = 2.248$ " | $I_b = 228.5$ " |
| $E_{ca} = 2.400$ " | $I_c = 312.2$ " |
| $P_{ca} = 371.49$ kilowatts, | $P_{bc} = 511.30$ kilowatts |

from (38),

$$P = 371.49 + 511.30 = 882.79 \text{ kilowatts.}$$

from (39) and (40),

$$\text{Cos } \alpha = \frac{371.49}{214.8 \times 2.400} = \cos\,(43^\circ\ 54')$$

$$\text{Cos } \beta = \frac{511.30}{228.5 \times 2.248} = \cos (5° \, 36')$$

whence,

$$\text{Sin } \alpha = \sin (43° \, 54') = 0.6935$$
$$\text{Sin } \beta = \sin \; (5° \, 36') = 0.0977$$

substituting in (35),

$$P_w = 214.8 \times 0.6935 \times 2.400 + 228.5 \times 0.0977 \times 2.248 = 357.46 + 50.18 = 407.64$$ wattless kilovolt-amperes.

Substituting these values of $P$ and $P_w$ in (7),

$$\phi = \tan^{-1} \left( \frac{407.64}{882.79} \right) = 24° \, 47'$$

therefore,

power-factor = cos (24° 47′) = 0.908.

## DISCUSSION ON "THREE-PHASE POWER-FACTOR." ATLANTIC CITY, N. J., JUNE 30, 1908

**Comfort A. Adams:** I think that at least a part of Mr. Burt's demonstration may be rendered less mathematical, to the advantage of one's physical conception of the problem. I refer to that part leading up to equation (34) which is the algebraic statement of the validity of the ordinary method of measuring three-phase power by means of two wattmeters.

Since in any three-wire system the algebraic sum at any instant of the three currents counted positive in the same direction along the circuit is zero, one of these currents may be legitimately looked upon as the common return for the other two, since when counted positive backwards it is equal at each instant to the algebraic sum of the other two currents counted positive outwards. Any three-wire three-phase system may then be considered as a three-wire two-phase system.

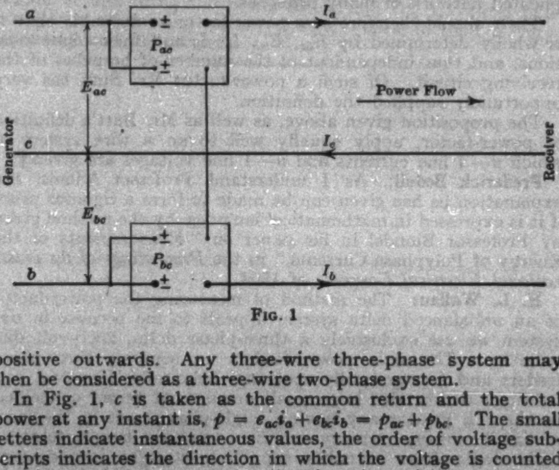

FIG. 1

In Fig. 1, *c* is taken as the common return and the total power at any instant is, $p = e_{ac}i_a + e_{bc}i_b = p_{ac} + p_{bc}$. The small letters indicate instantaneous values, the order of voltage subscripts indicates the direction in which the voltage is counted positive, and the arrows the directions in which the currents are counted positive.

What is true of the instantaneous values of the powers is true of their average values and of the readings of the wattmeters; or using Mr. Burt's notation, $P = P_{ac} + P_{bc}$. No assumption is here made as to the shape of the electromotive force or current waves. If the power flow is from left to right in both circuits, both wattmeters will give positive deflections when connected as shown. If one gives a negative deflection when so connected, it indicates a backward flow of power in that circuit and the reading of this instrument, when its pressure-coil connections have been reversed, must be subtracted from that of the other wattmeter to give the total outward flow of power.

Thus the point of view involved in this proof (if it may be dignified by that name) not only emphasizes the direction of power flow and its relation to the relative direction of current and electromotive force, but it also points out a positive method of connecting the two wattmeters into the circuit.

The proof given above is only a special statement of the more general proposition* that if in any three-wire system, (Fig. 1), the currents $i_a$ and $i_b$ and the simultaneous electromotive forces $e_{ac}$ and $e_{bc}$ are given for any instant, the system is for that instant completely determined in all its vital aspects, and that it is entirely immaterial as to how the three wires may be interconnected in the receiving apparatus, which may be two-phase, single-phase, three-phase star, three-phase delta, or a complicated network of many branches.

There should therefore be a power-factor so definable that it is wholly determined by $E_{ac}$, $E_{bc}$, $I_a$, $I_b$ and their phase relations, and thus independent of the number of branches of the receiving circuit. Of such a power-factor Mr. Burt has very opportunely supplied the definition.

The proposition given above, as well as Mr. Burt's definition of power-factor, apply equally well to an $n$ wire system of which $n-1$ line currents and $n-1$ line voltages are given.†

**Frederick Bedell:** As I understand Professor Adams, the explanation he has given can be made to form a rigorous proof if it is expressed in mathematical language by the method given by Professor Blondel in his paper on "Measurements of the Energy of Polyphase Currents" in the *Proceedings of the International Electrical Congress of* 1893.

**H. L. Wallau:** The method of measuring the power-factor of an unbalanced delta system appeals to me because in our system we use exclusively a three-phase delta, 2300-volt distribution. The main power feeders are separate three-phase feeders and are, generally speaking, balanced. However, our lighting circuits also have small amounts of power connected to them, a great many having single-phase loads in the form of small motors, mercury rectifiers, and arc lamps, together with single-phase branches supplying straight incandescent loads. For that reason our lines are to a greater or less extent unbalanced, and it has been of a great deal of importance to us to obtain an average power-factor which would truly represent the conditions on any particular feeder.

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* At the time of the oral discussion of this subject at Atlantic City the writer was convinced and stated that the proposition given above covered also the proof leading up to Mr. Burt's equation (35), but while the conviction remains, he has been unable to see the connection clearly enough from the physical point of view to express it in simple non-mathematical form.

† "Polyphase Power Measurement" by C. A. Adams, Electrical World Jan. 19, 1907, p 143.

I think that in all cases where similar systems are being used, the power-factor on the system, as a whole, can be closely approximated by obtaining power-factor on various feeders. I have used various approximations to get at the average power-factor on the sub-station, for the purpose of determining the proper size of rotary condenser to be installed, to bring the power-factor up to such a value as would give an economical transmission from the generator to the sub-station, and also under certain cases the proper size of condenser to be installed on the customers' premises, in order to bring the power-factor up, sometimes, from a value as low as fifty per cent. to what might be called a livable value, one commercially practicable.

**B. A. Behrend:** I think that Messrs. Adams and Bedell are correct in regard to their simple way of proving the time-honored method of measuring the power-factor and the kilowatts of a three-phase alternating-current circuit. Their method is very interesting and instructive.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 30, 1908.*

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# SOME ENGINEERING FEATURES OF THE SOUTHERN POWER COMPANY'S SYSTEM

BY J. W. FRASER

It has been aptly stated that in order to build a hydroelectric power system there are three fundamental requirements:

1. A sufficient source of power.
2. A market for the sale of power within economical transmitting distance.
3. The necessary capital.

It is not the intention of the writer to discuss these three fundamentals in a general way, but to take a concrete example and show how the conditions governing the sale of power must affect the design of the system as exemplified in that with which he is connected, and to describe in a general manner this system proposed ultimate extension of the same.

We will assume for the purpose of this paper a sufficient source of power, as any discussion of the hydraulic conditions would lengthen this paper undesirably. In passing, attention will be called only to the location of the various sites shown on the map, Fig. 2. These aggregate not less than 150,000 h.p. One only, the Catawba plant of 10,000-h.p. capacity was partly developed. The nine others are scattered along the Catawba River for a distance of 120 miles, with one on the Broad River about 30 miles west of Catawba Station.

In discussing the market at the time when the Southern Power Company was organized (1905), attention is first called to the map, Fig. 1, showing the location of cotton mills in the South, on which is shown a rectangle covering an area of 140 miles north and south by 180 miles east and west, about equally distributed in North and South Carolina. This area

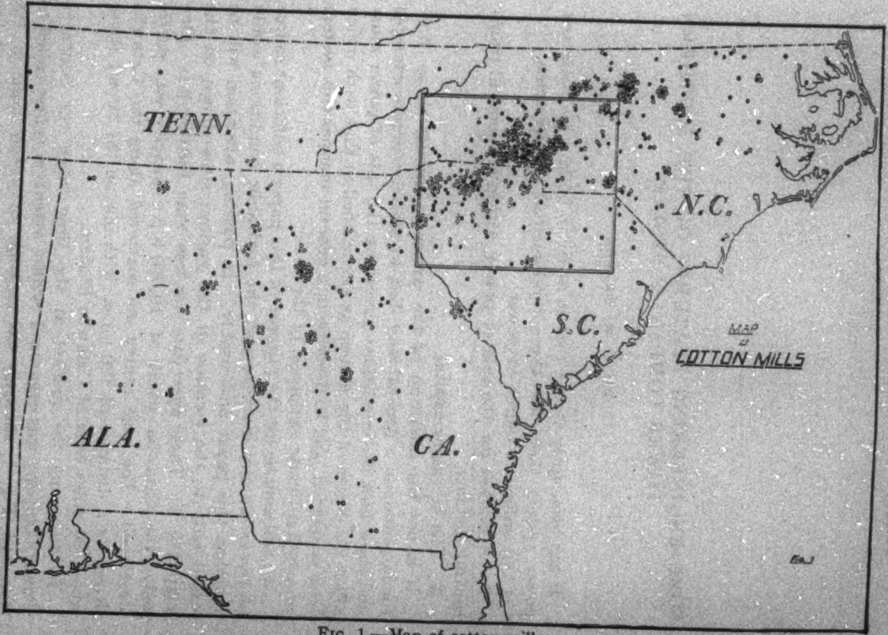
MAP of COTTON MILLS
TENN.
N.C.
S.C.
ALA.
GA.

FIG. 1.—Map of cotton mills.

● Built before 1892 ○ Built between 1892 and 1907 is enlarged on the map, Fig. 2. It will be noted that it contains the largest number of mills that can be taken in by any such area in the South. It represents a power consumption of approximately 200,000 h.p., one-fourth of which is water power. It is all within easy transmitting distance from the various power sites referred to in the above paragraph.

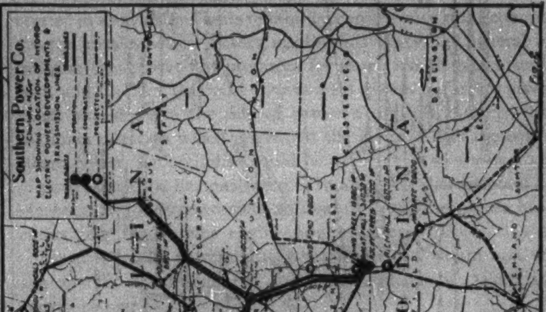

FIG. 2.—Map of Southern Power Company's transmission lines.

Before investing in these sites a careful investigation showed the average cost of power to be in the neighborhood of $34 per brake h.p. year of 3366 hours; that, although a few of the larger mills had got this cost down to $30, the majority of the smaller mills could not produce power for much less than $40. With

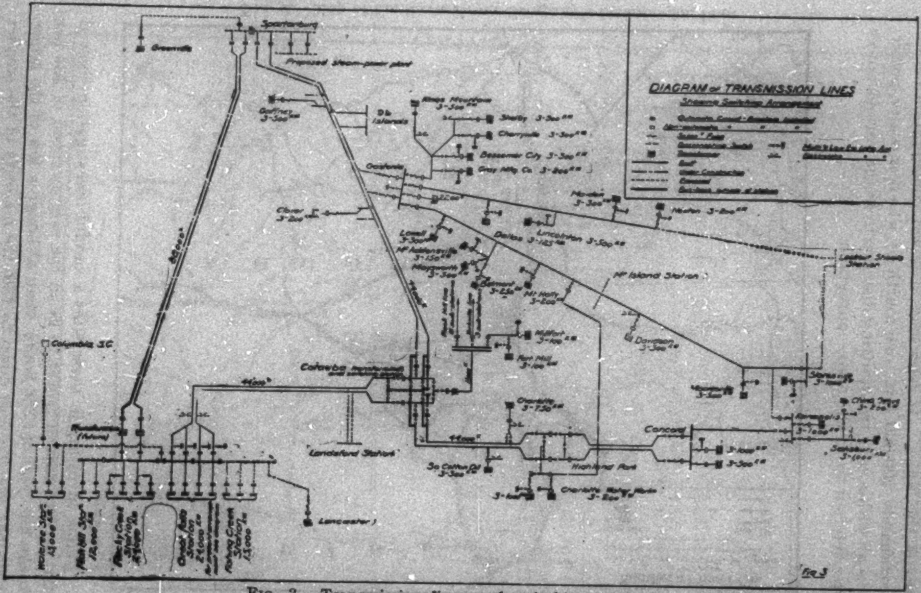
DIAGRAM OF TRANSMISSION LINES
Spartanburg
Greenville
Proposed steam-power plant
Gaffney 3-300 KW
99 Islands
Kings Mountain 3-300 KW
Shelby 3-300 KW
Cherryville 3-300 KW
Bessemer City 3-300 KW
Gray Mfg. Co. 3-200 KW
Gastonia
Clover 3-200 KW
Morden 3-300 KW
Newton 3-200 KW
Lincolnton 3-300 KW
Dallas 3-125 KW
Lowell 3-300 KW
McAdenville 3-150 KW
Mayworth 3-300 KW
Belmont 3-250 KW
Mt Holly 3-200 KW
Mt Island Station
Lookout Shoals Station
Davidson 3-300 KW
Mooresville 3-300 KW
Statesville 3-1000 KW
China Grove 3-200 KW
Kannapolis 3-1000 KW
Salisbury 3-1000 KW
Concord
3-100 KW
3-300 KW
Millfort 3-100 KW
Fort Mill 3-100 KW
Charlotte 3-750 KW
Highland Park
So. Cotton Oil 3-300 KW
Charlotte Water Works 3-200 KW
3-100 KW
Catawba transforming and switching station
44000
Landsford Station
Lancaster
Columbia S.C.
Wateree Sta. 41000 KW
Fishing Creek Station 15000
Great Falls Station 24000 KW
Rocky Creek Station
Rich Hill Sta. 12000 KW
88000
Fig. 3

FIG. 3.—Transmission lines and switching arrangements.

coal at $3.50, power could not be distributed for less than $28, even from large central steam stations. Experience acquired from the Catawba station and some smaller stations, to the records of which access was had, showed a fair margin of safety after transmission and other losses were taken into account.

True it is that in recommending investment in these sites it had to be considered that although the electric drive had demonstrated in some instances its reliability, convenience, and economy, yet the unsatisfactory history in other instances, the general impression that power was produced for much less than it actually cost, and the fact that mill owners were averse to further investment, would make the sale of power a difficult matter. Still the main question which interested the investor was the cost of steam power, for prejudice could be overcome and the real cost of power could be demonstrated. In a further discussion of the market, it is found convenient to treat of it under separate heads embodying the various engineering features.

*Frequency.* In determining what frequency would best suit the market conditions the following had to be taken into consideration:

*a.* That the 60-cycle generators at Catawba station and some 8000 to 10,000 h.p. in induction motors receiving power from that station would have to be rewound or exchanged, if other than 60-cycle were used, on account of the fact that separate lines would be too expensive and would complicate matters. Motor-generators would make the cost prohibitive, because of the large number of distributing points.

*b.* That 60-cycle motors to a total of approximately 8000 h.p. were driving mills in the vicinity of proposed lines, which load might be obtained, provided the frequency were the same.

*c.* That there were also quite a few small city plants operating at 60 cycles. At present this might not amount to much, but the growth of these cities had to be considered, particularly in reference to arc lighting. In three years 2500 arc lights have been put in service, and if motor-generators had had to be installed the cost to small mill towns would have been excessive.

*d.* That a high frequency would give a better power-factor, due to the leading charging current.

*e.* That 25-cycle generators, transformers, and motors would cost at least 10%, 25%, and 10%, respectively, more than 60-cycle generators, transformers, and motors.

*f.* That there was very little prospect in the near future of a synchronous converter or railway load, and there were plenty of cotton mills in the district covered to use all the power which could be generated from the rivers.

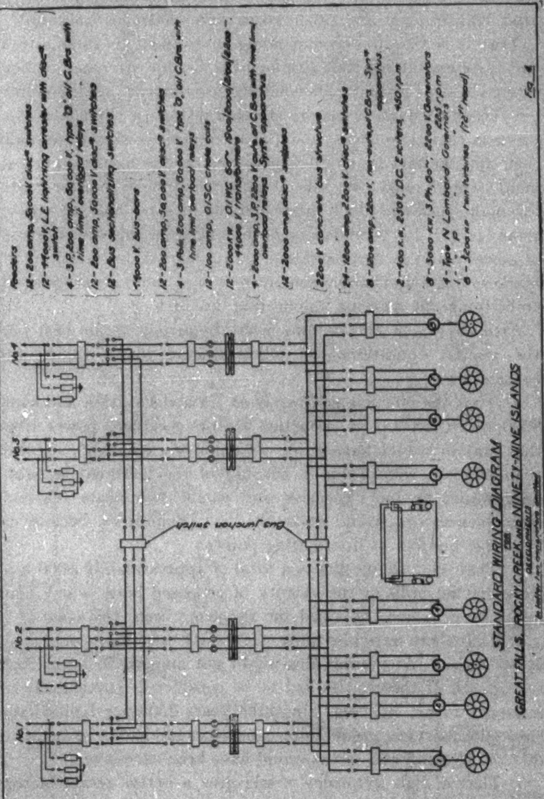
Feeders
12-200 amp, 50000 V disc^n switches
12-44000 V, L.E. lightning arrester with disc^n switch
4-3 P, 200 amp, 50000 V, type "D" oil C Brs with time limit overload relays
12-200 amp, 50000 V disc^n switches
12-Bus sectionalizing switches
44000 V bus-bars
12-200 amp, 50000 V disc^n switches
4-3 Pole, 200 amp, 50000 V type "D" oil C Brs with time limit overload relays
12-100 amp, O.I.S.C. choke coils
12-2000 K.W. O.I.W.C. 60~ 1900/2000/2100/2200 - 44000 V Transformers
4-2000 amp, 3 P, 2200 V auto oil C Brs with time limit overload relays Syn^g apparatus
12-2000 amp disc^n switches
2200 V concrete bus structure
24-1200 amp, 2200 V disc^n switches
8-1200 amp, 2200 V, non-auto oil C Brs Syn^g apparatus
2-400 K.W., 250 V, DC Exciters 450 r.p.m
8-3000 K.W., 3 Ph, 60~, 2200 V Generators 225 r.p.m
4-Type N Lombard Governors
" " P "
8-5200 H.P. twin turbines (72" head)
Fig 4
No. 1
No. 2
No. 3
No. 4
Bus junction switch
STANDARD WIRING DIAGRAM
FOR
GREAT FALLS, ROCKY CREEK AND NINETY-NINE ISLANDS
DEVELOPMENTS

FIG. 4.—Type of station wiring diagram.

Against the above is the extra line-drop, but when all the developments are completed very little power will be transmitted more than 40 miles, except over trunk-lines where the drop may be taken care of by raising the generator electromotive force. For instance, the voltage at Catawba and at Spartanburg, two centers of distribution, can always be maintained at 44,000 volts.

These considerations seemed to favor 60 cycles, but as exact figures were necessary in this case the following rough calculation was made: the saving in cost of generators and transformers amounted to $75,000, and if the saving in copper due to increased power-factor is added the total will be in the neighborhood of $100,000.

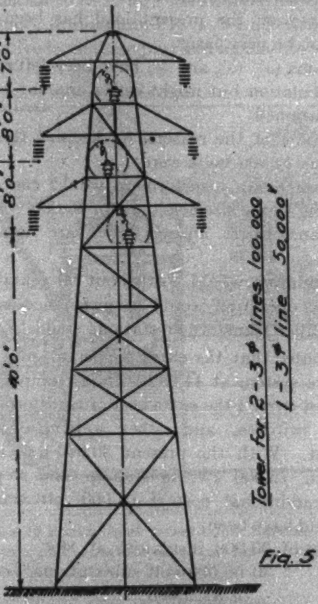

FIG. 5.—88,000 volt tower.

There is an additional loss of about 10% of the loss which there would have been at 25 cycles, and the integrated loss over the present lines when fully loaded will be in the neighborhood of 27%. In power this amounts to 10% of 27% of 26,000 kw. =

700 kw., which at $5.00 per kw. is $3500.00. Capitalized at 6%, this amounts to $60,000—a balance of $40,000 in favor of 60 cycles. It is possible that a very careful analysis might show this loss to be a little greater, but the error cannot be over 25% as the integrated loss referred to has been taken over a period of six months and covers losses from generators to meters on load. The only other error which could be made would be in estimating the line-drop when the present lines were fully loaded, but as the drop on the present load has been measured the error could not be very large.

Considerations (*a*), (*b*), and (*c*) have been left out of the above numerical calculation but might easily amount to several times the figure mentioned.

*Voltage.* Some of the reasons for keeping the electromotive force as low as 44,000 volts were:

*a.* That 44,000-volt transformers would cost from 18% to 33%, depending on the size, less than for 66,000-volt transformers.

*b.* That transformers and switches are more reliable at 44,000 volts.

*c* That insulators would cost about 80 cents less each.

*d.* That line operation would be more successful.

*e* That smaller transformer stations could be built.

It was estimated that the extra copper to give the same drop over the entire system at 44,000 volts as compared with 66,000 volts would not exceed the extra cost of transformers, insulators, sub-stations, switches, and other apparatus. The estimate proved correct. With the present 30,000-h.p. load there are on the system 72,000 kw. in step-up and step-down transformers; the additional cost if 66,000-volt transformers had been used would have been $64,000

| | |
|---|---|
| Additional cost of 30,000 insulators at 80¢.......... | 24,000 |
| " " " 30 66,000-volt sub-stations, *i.e.* 20% of $125,000.................... | 25,000 |
| " " " step-up transformer stations, *i.e* 10% of $200,000................ | 20,000 |
| | $133,000 |
| Against this is the saving in copper in the transmission line had the higher e.m.f. been used, roughly 50%.. | $130,000 |

This shows a saving of only $3000 but the present lines will carry a great deal more power than they are now carrying, which will increase this amount materially.

One line only of those proposed stands out as an exception, the trunk line running from Great Falls to Spartanburg and thence to Greenville, about 100 miles in length. This line now under construction will be so built that when overloaded at 44,000 volts delivered electromotive force it can be changed to 88,000 volts (*i.e.* 100,000 volts at generating station). This will be accomplished at a very small additional expense by mounting pins and insulators similar to those now used on our wood-pole lines on the towers as shown in diagram, Fig. 5, for after conversion to a higher electromotive force these pins and insulators can be used on 44,000-volt lines, or this line may be permanently used for local distribution. The intention is that this 88,000-volt trunk-line will not be tapped at any point except at Spartanburg. This could be done more easily by using 100,000-volt suspension-type insulators, but it is felt that by the time it is necessary to change to the higher electromotive force there may be enough improvement made in these insulators to warrant the extra expense which would be incurred.

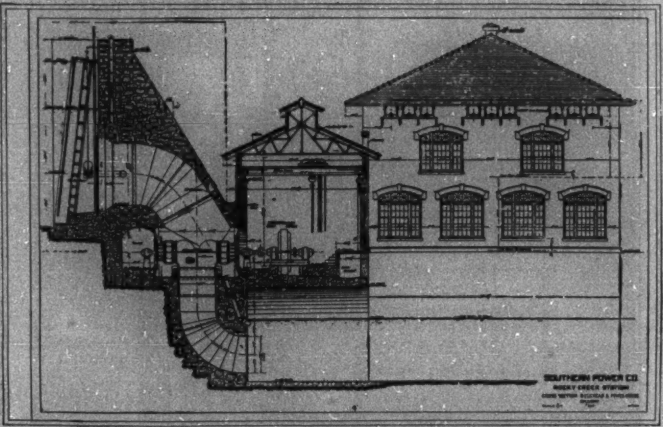

FIG. 6.—Section of Rocky Creek power house showing racks, gates, intake and tunnel for inner turbine bearing

*Transmission lines.* Further examination of the transmission-line map will show that two-thirds of the obtainable power is in the neighborhood of the Great Falls development. This position was selected as a main switching station, the idea being to mass the output of Great Falls, Fishing Creek, Rocky Creek, and Rich Hill at this point on outdoor bus-bars and control the line switches from the operating room in this station.

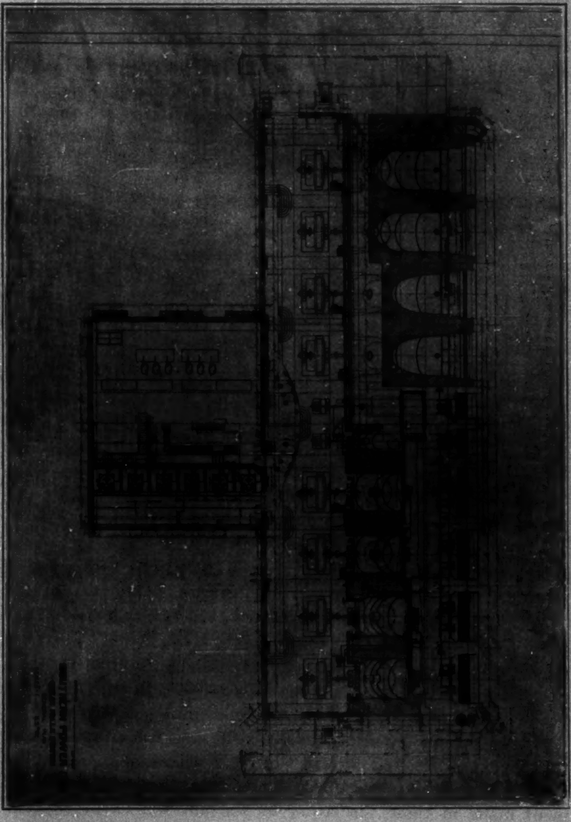

FIG. 7.—Plan Great Falls and Rocky Creek stations showing arrangement of generators, transformers high- and low-tension switches

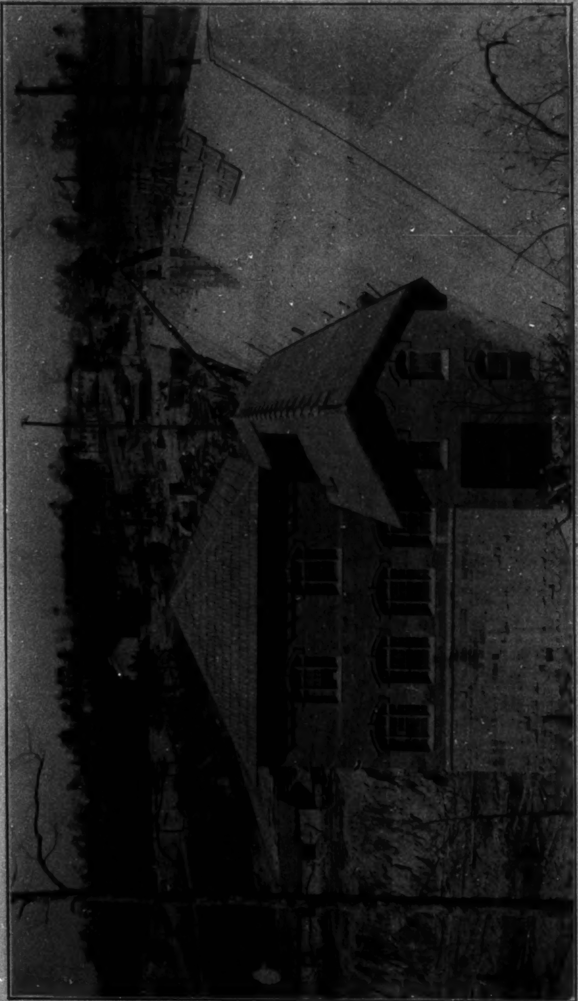

FIG. 8.—Outside view Great Falls station showing bulkhead wall and transformer house with line openings

FIG. 9.—Great Falls dam, showing racks, head gates and method used to obtain long spillway

The generators and transformers were designed to operate continuously at 85% power-factor to take care of an induction motor load, and at 115% normal electromotive force to take care of line-drop as the load increased. The main trunk line, from Great Falls to Catawba Station will take care of 20,000 kw. at 85% power-factor, with a line-drop of 13.5% and a loss of 7.25%. This represents the economical section of copper at 20 cents per pound with power costing $5 per kilowatt-year.

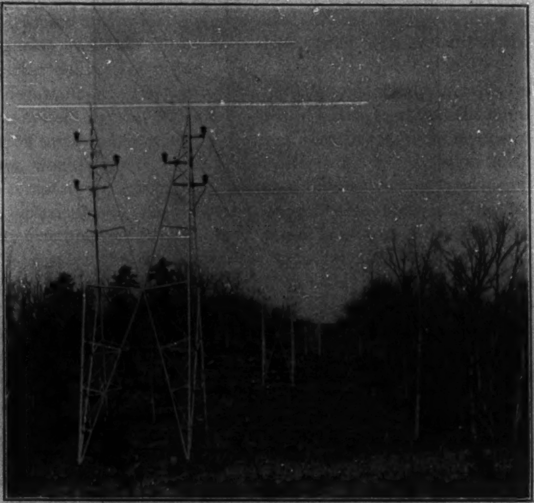

Fig. 10.—Main line steel tower.

It should be pointed out before leaving the subject of transmission lines, that the impossibility of making contracts with mill owners on account of their skepticism with regard to the electric drive, before the greater part of the present lines was actually built, made estimates on the amount of power to be sold in any one territory so difficult that the location and size of transmission lines could not be determined even approximately. In other words, where and in what amounts power was to be sold was a very uncertain matter.

This brought up the question of wood-pole lines versus steel towers. A little consideration showed that if the cost of towers per additional foot in height erected were $7.00 and copper were at 20 cents per pound, a No. 0 B. & S. gauge would be the smallest wire which could be strung economically on account of the increased sag in wires below this size for 500-ft. spans; that a single-circuit tower line would cost approximately twice as much as a pole line and would last probably twice as long; that a double-circuit tower line would cost very little more than a double-pole line; and that it would be more economical for cotton mills to shut down for a small percentage of time than to pay the additional price for power which would be necessary to cover the extra expenditure for steel tower lines. It therefore seemed good practice to build main trunk-lines of

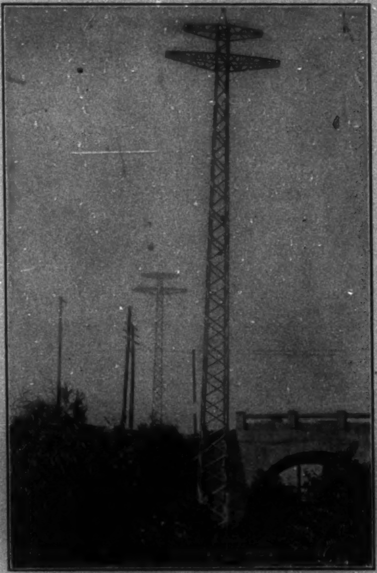

Fig. 11.—Steel pole used for city work

steel towers and all single lines below No. 0 gauge of wood poles.

Still another factor increased this difficulty. One large development under construction and several others recently financed by competing companies tended to make mill owners hold off for better prices. I refer to this merely to show how such a matter may affect the design. Considerable discussion resulted as to whether Great Falls and Rocky Creek should not be made into one development by means of a canal and pipe lines. This would take at least as long again as to develop one source and would cost the same as separate developments. Decision was made for separate developments on account of the quicker delivery of power.

*Sub-stations*. The first motor installations in cotton mills on this system were of 550 volts, but it was soon seen that the number of small transformer sub-stations, besides complicating operation, would cost excessively, and after some investigation 2000-volt motors were recommended for all mills converting from steam to electric drive. These installations proved so successful that to-day over one-half the total horse power in motors is at 2000 volts. The cost of the conduit in the mills for 2000 volts is nearly offset by the smaller wire used, and this electromotive force permits all mills within a radius of two miles to be fed from one sub-station. Many new mills, on account of using individual drive and consequently motors below 30 h.p., are compelled to step-down at least a part of this current to 550 volts.

The sizes of transformers in sub-stations are as follows:

| 11,000 volts (All purchased before beginning of new development) | | 44,000 volts | |
|---|---|---|---|
| 5 Stations with | 3–100 kw. | 1 Stations with | 2– 100 kw. |
| 5 " " | 3–125 " | 1 " " | 3– 125 " |
| 3 " " | 3–150 " | 1 " " | 3– 150 " |
| 1 " " | 3–200 " | 7 " " | 3– 200 " |
| 1 " " | 3–250 " | 8 " " | 3– 300 " |
| 1 " " | 3–500 " | 5 " " | 3– 500 " |
| | | 1 " " | 3– 750 " |
| | | 4 " " | 3–1000 " |
| | 7,575 kw. | | 34,175 kw. |

Many of the 44,000-volt sub-stations below 900 kw. are now partly or wholly owned by customers, as are also some of the

900-kw. and 1500-kw. stations, most of the mills in one town preferring to take shares rather than pay the additional price for power necessary when the station is owned by the power company. The customer usually requests that the power company buy and install the sub-station apparatus. The customer gets the benefit of any experience which the power company may have and obtains sub-stations at a minimum cost. In the larger towns where attendants must be kept it has been found more satisfactory for the company to own the sub-station. The power company has discountenanced the buying of transformers below 200 kw. on account of the high cost of completed stations per kilowatt. In the case of a 900-kw. station (3-300-kw. transformers) when the transformer cost is two-thirds of the total and 150-kw. cost 50% more per kilowatt than 300-kw. transformers, the power company has taken a share in the station rather than have the customer install the small transformers. The companies consider this to be to their interest in view of the facts that they get all new mills and that the interest on the additional investment for two years would not pay the installation charges for substituting the large transformers when they were needed.

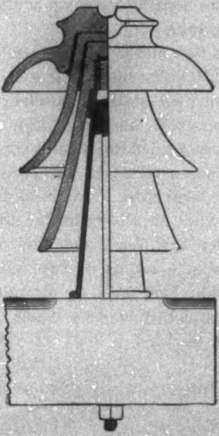

FIG. 12.—44,000 volt insulator.

All sub-station transformers have been purchased under a standard specification in order that a few stock transformers which the power company has made it a policy always to keep on hand may serve as spare apparatus in case of accident.

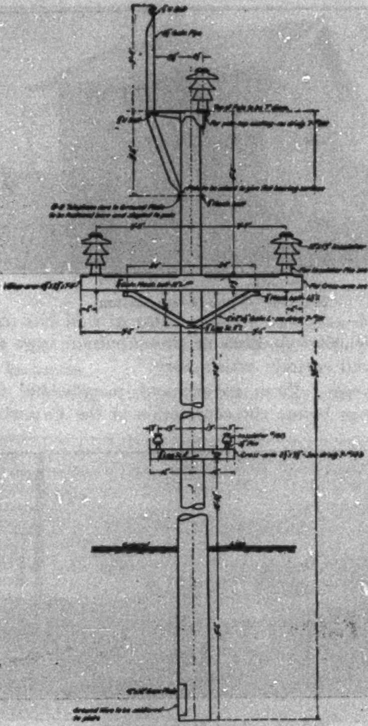

FIG. 13.—Standard wood pole

It is believed that no transformers below 300 kw. and very few below 500 kw. will have to be purchased in the future; for with the present rapid growth of cotton mills and the use of 2200-volt distribution in the towns where sub-stations are located, the small transformers will have to be exchanged for larger ones, the smaller ones being available for the new sub-stations carrying small loads.

It may be of interest to some to know that there are now on our lines 114 50,000-volt fuses of the expulsion type and that they have proved entirely satisfactory.

Fig. 14.—Type of sub-station

*Secondary power.* From government records and from six years of gaugings before the completion of the Catawba plant, together with two years' operating experience, the flow of the Catawba river had been pretty well determined. The question which presented itself most forcibly was whether to develop the average minimum 12 months' flow, or to develop for 10 months, 8 months, or less, and to supplement with steam power—a

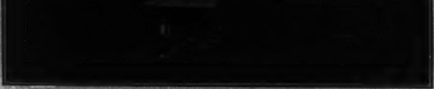

Fig. 15.—Type of sub-station

problem which has to be determined by the first cost of development and by local market conditions.

Owing to limited library facilities at his command, the writer was unable to ascertain if this question had been touched upon elsewhere and how in other cases it had been determined, and so trusts that a few words with reference to this particular case will not be amiss.

FIG. 16.—Type of sub-station

In the following calculations where the cost of primary and secondary power is taken at a fixed rate, the intention is not to convey the idea that these are actual figures but relative figures which will serve the purpose of this paper.

FIG. 17.—Catawba dam

There are many different solutions to the problem of ascertaining the amount of secondary power which may be economically developed. At one of our developments it was found that the average minimum primary power was in the neighborhood of 16,000 kw. and that the increase per month of secondary power was in the neighborhood of 12.5%; *i.e.*, 2000 kw. per month. In other words, if secondary power were to be developed for 8 months' sale, the total development of primary and secondary power would be 24,000 kw. If this secondary power can be sold without an auxiliary steam plant, the amount of secondary power which may be developed economically depends only upon whether or not the price received for such power will cover interest and profit on the investment; that is, the investment which is over and above that for developing primary power: but if a steam plant has to be maintained the amount of secondary power to be developed depends also on the cost of steam power. It is very clear that the cost of secondary power is practically the same, whether it is sold for 11 months or 1 month. With this cost, say at $10.00 per horse power delivered, steam at $28.00 per horse power-year ($6.00 interest and depreciation, $22 for coal, operating expenses, etc.), if interest and depreciation on the steam plant is entirely chargeable to the months when steam plant is in operation, then

FIG. 18

$$\text{Cost of steam power per month} = 1.83+\frac{6}{x}$$

When $x$ = the number of months in operation.

Amount of secondary power to be developed = 16,000 kw. $\times \frac{12.5x}{100} = 2000x$ or $\frac{2000x}{0.746}$ h.p.

$$\text{Cost of steam + secondary} = \frac{2000x\,(1.83+\frac{6}{x})\,x + 2000x \times 10}{0.746}$$

$$= \frac{2000\quad(1.83x^2+6x+10x)}{0.746}$$

If power is selling at $20, profit

$$= \frac{(2000\,x\,20-\left\{2000\ (1.83x^2+16x)\right\}}{0.746}$$

$$= \frac{2000\ (20x-1.83x^2-16x)}{0.746}$$

$$\text{(For max.)}\quad \frac{dy}{dx} = 3.66x-4$$

$$x = 1.1 \text{ month}$$

On this basis maximum profit would be made on 2200 kw. secondary development.

A more practical method under existing conditions seems to be to charge the interest and depreciation of steam plant to the operating expense of the system, inasmuch as the steam plant is an insurance against a partial shut-down and makes spare units unnecessary, and in the case of steam turbines, when run as synchronous motors, saves copper because it brings up the power factor. The above equation now becomes:

$$\text{Cost of steam + secondary} = \frac{2000x\ (1.83x) + 2000x \times 10)}{0.746}$$

$$= \frac{2000\ \ (1.83x^2+10x)}{0.746}$$

$$\text{Profit} = \frac{2000\,x\,20-\ (2000\ (1.83x^2+10x)}{0.746}$$

$$= \frac{2000\ (20x-1.83x^2-10x}{0.746}$$

$$= \frac{2000\ (10x-1.83x^2)}{0.746}$$

$$\text{(For Max.)}\quad \frac{dy}{dx} = 3.66x-10$$

$$x = 2.75$$

Maximum profit on this basis would be made on 5500 kw. (35%) secondary development.

Had $24.50 been taken as the selling price of power, $x$ would equal 4 months, or the total development should be made for 150% of mean average low water. Although power from hydroelectric plants has been selling in the Carolinas for less than this latter figure there is no doubt that reliable service demands this price.

There is another argument in favor of developing for 150% mean average low water. If it costs only one-half as much to develop secondary power as primary, twice the loss can be allowed on transmission lines; or, in other words, one and one-half times the power can be transmitted during secondary power seasons. Now, if the transmission lines are figured for an economical loss when transmitting primary power only, secondary power to the extent of 50% of the primary power can be developed without additional copper. This only holds good when the auxiliary steam plants can be built in the neighborhood of distribution centers whose consumption of power is equal to the amount of secondary power.

Many mills which had steam plants already installed made contracts for secondary power for eight months in the year, but after a few months' operation by electric drive their owners found the production so much increased and their labor and other troubles so much lessened that many of them desired to change their contracts to primary power. The result of this is that the plans for a supplementary steam plant are now in course of preparation. The initial installation will be 15,000 kw. and will be located at Spartanburg, S. C., near the southern end of the system, 64 miles from the main switching station at Great Falls on the 88,000-volt line. The ultimate installation is expected to reach 40,000 kw., divided between this point and some point near the eastern end of the system. It is thought better to divide the plant for safety and in order that the line loss may be kept as low as possible.

# DISCUSSION ON "SOME ENGINEERING FEATURES OF THE SOUTHERN POWER COMPANY'S SYSTEMS." ATLANTIC CITY, N. J., JUNE 30, 1908.

**J. H. Finney:** I believe that many of us here fail to realize the actual value of the work that has been done by the Southern Power Company in the south. I think that there are not many electric plants in this country that I have not seen at one time or another, and I believe the work that has been done in developing the water-power system of the Catawba river by the Southern Power Company is as creditable as any similar work in the United States. It is well worth while to go down and see that Great Falls plant, the Rocky Creek plant, and the others there.

**W. S. Lee:** Perhaps a good many engineers do not know the conditions that we have to meet on southern streams. There is an erratic flow, a flood discharge on several of these plants one hundred times the minimum discharge; this means quite a problem in designing the structure from the hydraulic end, as well as trying to apportion the station equipment so as to use the secondary power to the best advantage. We have studied this condition carefully, and while we have adopted the plan of putting in station equipment about one and one-half times the minimum low-water requirements, naturally there is a possibility of even changing that, due to the fact that a great many southern cotton mills have efficient, large steam plants. We are now offering power for sale on a six months' basis, which we call six months' secondary power, at a much lower price. This six months' power is an inducement to the large plants, which can run six months on steam and six months on water power. In some years the water flow is a little greater, and the mills can then be operated by water power eight months, or even ten months, and on rare occasions, twelve months in the year.

We first had a great many 550-volt motors on the cotton-mill work, and were endeavoring to make the voltages multiples. We saw at once that in cotton-mill work it was not advisable to install a 44,000-volt sub-station for each mill, consequently almost all installations are now using 2200-volt motors. We have towns in which we operate seven or eight mills from 200 to 500 h.p. each, where it is possible to locate one sub-station. All our transformers are wound for 550 and 2200 volts on the low-tension side, and 11,000, 22,000, and 44,000 volts on the high-tension side.

Reference to the map will show the location of the Great Falls station, Rocky Creek station, and Fishing Creek station. Great Falls station being between the other two, it is our intention to feed Rocky Creek and Fishing Creek stations into a common switch house or bus-bars, which will be located at the Great Falls station. This will enable the attendants at Great

Falls station to control all lines or feeder circuits. We are also designing an 88,000-volt transmission line from Great Falls to Spartanburg, S. C. The transformers and control of lines for this voltage will also be handled by attendants at Great Falls station.

**D. B. Rushmore:** The plant of the Southern Power Company is one of considerable interest. The voltage of the plant, 44,000, was the maximum conservative voltage at the time of installation. At present one would use a higher potential for such conditions. Efforts should be made to standardize transmission voltages. Below 44,000, the figures are fairly well fixed; above, there exists a wide variety of voltages. We must either decide on delta-star combinations, or else choose some arbitrary figure. For high-voltage transmission work one does not change the system of connections from delta to star after the first decision has been made; therefore an arbitrary decision on multiples of eleven seems the most logical basis. The following voltages are recommended for transmission work: 6600, 11,000, 22,000, 33,000, 44,000, 66,000, 88,000, 110,000, and 165,000; 66,000 is already in operation in so many places that it already has an existence; 88,000 is taken as the double of 44,000. On transmission lines it is often desirable to double the voltage and to wind transformers for the higher voltage, using them for parallel connection on the lower voltage. A large number of plants are now being installed at or about 100,000 volts. It seems desirable to fix this figure at 110,000, these voltages being the voltages at the generating station. 165,000 is proposed for the next step.

One of the factors which has entered into the successful operation of this plant has been the use of 60,000-volt insulators on the 44,000-volt line. The greater margin of safety is one of the results of experience in this line of work.

It is to be noted that this system employs a delta connection on the transformers on the high-voltage side; also that a compromise is effected concerning the use of transformer compartments, and that the high-tension wiring is entirely open.

A feature of especial interest is the use of expulsion fuses instead of automatic switches for protecting the sub-station apparatus. It is understood that this feature has been very satisfactory.

**P. M. Lincoln:** I agree with Mr. Rushmore that it is desirable, if possible, to fix high-tension voltages in advance of their use, but I am not sure that it is best to eliminate the 88,000 volts. There are a number of plants in which this voltage is proposed; the reason for it is that the plants are to go in at first at half that voltage, 44,000 volts, while the amount of power called for is small, but they are being installed with the intention of eventually doubling this voltage. The fact that there are two different but obvious methods by which transmission voltages may be increased is responsible for the existence of the odd voltages.

Voltages may be increased either by doubling the previous voltage or by throwing delta-connected transformers into a star connection. In the former case the factor of increase is two and in the latter $\sqrt{3}$. With this constant tendency toward odd transmission voltages the adoption of standards becomes all the more important.

In regard to the question of delta- versus star-connected transformers, I think that the selection of delta or star connection depends largely upon whether the neutral of the high potential system is to be grounded or not. If the grounded neutral is to be used, the star connection of the high-tension side is essential to obtain a neutral point. If the grounded system is not to be used, there is not much choice between the delta and the star. It is true that the star-connected transformers are somewhat less in cost than a similar set of delta-connected transformers, but this is not a controlling advantage. The whole thing hinges upon the larger question of whether the high-tension transmission system is to have a grounded neutral or not.

**Chas. P. Steinmetz:** I desire to commend the engineers who have designed this plant, on their conservative way of choosing transmission voltages and transmission design, which ought to go a long way to maintain the record of reliability of operation acquired by the smaller station, of which this big system is the successor. Many of us do not realize the enormous work which is being carried on in the electrical development of the South. We read, and have heard, for many years of the long-distance transmissions in the West and Central states. Great results have indeed been accomplished there, where coal is almost out of the question by reason of its price, and where the distances are long and the voltages high, but not all of us realize that similar development is going on in the South. The development may not be of greater magnitude, but it is under different conditions, in competition with steam. The southern plants do not supply mines and towns which do not mind an interruption once in a while; they supply consumers like city lighting plants or cotton mills, where it is a serious matter to shut down and throw hundreds, if not thousands of hands out of work. There more conservative voltages must be used, and while 100,000 volts may be all right in the West, they are a little high for the South.

It is very encouraging to see how a system of enormous magnitude, fully as large in kilowatt capacity and in extension over distances as any western system, has chosen 44,000 volts as the trunk-line voltage for transmission, using half or quarter thereof for the high-voltage distribution system, and leaving it for the future, when necessary, to use a line of double that voltage, 88,000 volts.

Fourteen years ago the first cotton mill was installed in the South with electric drive. It is hard to realize how the whole South has rapidly developed commercially, and how electric power is coming to the front. Water power systems are everywhere being developed. It is encouraging to see that this great development has been on conservative lines, and it is to be hoped, that as a result of the development of these systems, we will be able to say that long-distance transmission is as reliable as local distribution, and that it will not be necessary to say—among ourselves not to the public—that long-distance transmission is ideal where you get the power, but after all you never know whether you will get the power or not.

**P. H. Thomas:** I ask Mr. Fraser if he should not add to the advantages of the large secondary steam development, the extra capacity of reserve, in case of trouble?

One other question: Does the term "average minimum primary power" indicate power that could be actually developed with no steam auxiliary at all?

**J. W. Fraser:** Mr. Lee has answered the question as to the 44,000 volts, and higher voltage, which we expect to use, and he has also answered the question regarding the wiring diagrams. With regard to the fuses, we have something like one hundred and twenty-five 50,000-volt fuses in use, and have used them in all the sub-stations. They work very satisfactorily indeed.

Replying to Mr. Thomas's question; that is the average power obtained for a number of years without any secondary power at all which would be developed if we had no steam power.

**P. H. Thomas:** Will you describe the fuses more particularly?

**J. W. Fraser:** The enclosed fuse referred to is mounted on line insulators, which in turn are mounted on a treated board about 6 ft. long and 10 in. wide. The explosion takes place in a short metal barrel at the end of the fuse, which is 42 in. long, and is discharged through a fibre tube about 3 ft. long. The fuse is also used as a disconnecting switch.

With regard to voltage regulation, it does not matter what the voltage at the Great Falls station is, so long as the voltage at the Catawba station is maintained at 44,000. The main trunk line is not tapped between Great Falls and Catawba station, so that the voltage at the former station may be varied between 44,000 and 50,000 as the load changes.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 30, 1908.*

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# HIGH VOLTAGE MEASUREMENTS AT NIAGARA

BY RALPH D. MERSHON

In the autumn of 1896, the writer of this paper undertook an investigation of the phenomena existing when transmission line conductors are subjected to high alternating voltages. The work was carried on near Telluride, Colorado, and extended over a period of about a year. The results of this work were embodied in a report made by the writer in 1897.*

Through lack of the necessary facilities at Telluride, the work was not carried as far as seemed desirable and, after its discontinuance, I looked forward to taking it up again and obtaining additional data. This opportunity offered in 1903, and in the autumn of 1904, after the necessary apparatus had been obtained, the work was resumed at Niagara Falls, and the observations carried on more or less continuously until the summer of 1907.

In the meanwhile, Professor Harris J. Ryan† read before the Institute his paper bearing on this subject and embodying the results of investigations made by him of some of the points I had intended to cover, and a number of others which my facilities would not admit of closely investigating.

The present paper has mainly to do with the results of the work carried on at Niagara Falls, but in the treatment of these results, the work at Telluride and that of Professor Ryan will necessarily be referred to and discussed.

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*The investigation was undertaken for the joint interests of the Telluride Power Transmission Company and the Westinghouse Electric and Manufacturing Company. Part of the matter of the report was embodied in a paper read at the Fifteenth General Meeting of the American Institute of Electrical Engineers, June 30, 1898, by Mr. Chas. F. Scott, entitled "High Voltage Power Transmission."

† See paper entitled "The Conductivity of the Atmosphere at High Voltages," read at the 184th meeting of the American Institute of Electrical Engineers, Feb. 26, 1904.

The work at Niagara was made possible, in the first instance, by the generosity of three men; Mr. J. E. Aldred, Mr. Frederic Nicholls, and Mr. James Ross. Later, further support to the work was contributed by Mr. George Westinghouse, and by the African Concessions Syndicate of London. The major portion of the expenses of the work at Niagara was defrayed by the above contributors.

I desire to express my appreciation not only of the generosity of these contributors, but also of the completeness with which they entrusted the expenditures to my judgment and the kindly patience with which they have awaited results so long deferred by reason of the tedious, intricate, and often discouraging nature of the work. It is to be wished that engineering investigation might be more encouraged in a like manner and spirit. I hope the results obtained will appear to justify the contributors in this instance.

For convenience of treatment, the matter of this paper is arranged under the following heads: Equipment; Results of Measurements; Discussion of Results; Résumé and Conclusions.

## EQUIPMENT

The line experimented upon at Niagara had a total length of 2000 feet, although, generally, only half its length was used. It was supported upon wooden poles, spaced about 140 feet apart. At first, the line wires were supported upon insulators, but it was found that the loss over the insulators was so great, as compared with the air losses, and so variable that if any reliable results were to be obtained, it would be necessary to find some other way of supporting the line conductors. Finally, the line wires were suspended by means of paraffined cords attached to the necks of the insulators. As long as these cords were clean, the loss over them was negligible. As soon as they became dirty, they were replaced by clean cords. A portion of the line with the suspending cords is shown in Fig. 1. This line will hereafter be referred to as the " Experimental Line ".

In addition to the experimental line, use was made of a number of cross-arms equipped with pins and insulators, similar to those used on the experimental line. This miniature line had a total length of only a few feet, so that the air loss between its conductors was negligible, the loss upon it being due to the insulators only. This miniature line will be designated hereafter as the " Dummy Line ". It is shown in Fig. 2.

The following conductors were used.

ALUMINUM CONDUCTORS

| Circular mils | Number of strands | Diameter one strand inch | Outside diameter inch |
|---|---|---|---|
| 10500 | 1 | 0.1025 | 0.1025 |
| 20740 | 1 | 0.144 | 0.144 |
| 34600 | 1 | 0.186 | 0.186 |
| 51529 | 1 | 0.227 | 0.227 |
| 41800 | 19 | 0.0469 | 0.2345 |
| 42910 | 7 | 0.0783 | 0.2349 |
| 41750 | 37 | 0.0336 | 0.2352 |
| 103850 | 7 | 0.1219 | 0.3657 |
| 208200 | 7 | 0.1728 | 0.5184 |

COPPER CONDUCTORS

| | | | |
|---|---|---|---|
| 10420 | 1 | 0.1021 | 0.1021 |

The various types of insulators with which experiments were made are shown in Fig. 3 and will be referred to hereafter by the letters designating them in the illustration.

Two single-phase, 100,000-volt transformers were used, each having a capacity of 10 kilowatts. The endeavor was made to have the iron of these two transformers as nearly as possible identical as to loss, etc., for reasons which will be apparent from the description of the method of measurement employed. The two transformers were immersed in oil in the same boiler iron tank. They were of the core type, and had ground shields between the high-tension and the low-tension windings. The windings had taps for connecting the transformers, when desired, for polyphase transformation. The transformers had a number of special low-voltage coils, the use of which is explained below.

The power for the measurements was obtained from a surface-wound, single-phase alternator of the old 133-cycle type, belted to an induction motor and driven at about one-half speed. This machine gave very nearly a sine wave under almost all conditions. The intention was to run it at 60 cycles, but instead it was run usually at about 73 cycles.

The wattmeter made use of was one especially constructed

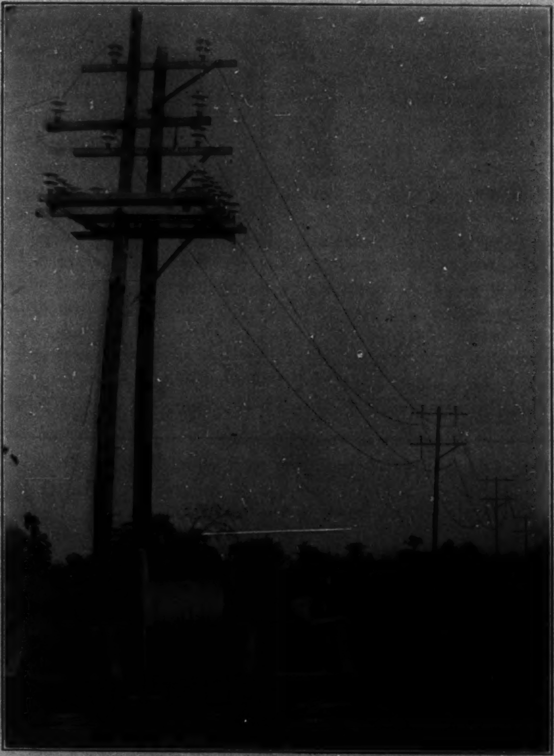


Fig. 1

for this purpose. It is shown in Fig. 4. It consisted of the regular Weston wattmeter movement and shunt resistance enclosed in a suitable wooden box, and an external field coil which could be slid over the wattmeter movement or away from it, so as to give an instrument of considerable range. The field coil was enclosed in a suitable wooden frame. This field coil consisted of two identical windings, the wires being wound side by side, so that the magnetic axes of the two windings would as nearly as possible coincide. In addition there was supplied with the wattmeter an extra field coil exactly like the one used with the wattmeter. This extra field coil was used as an air transformer, as described later on.

The type of barometer, thermometer, and sling psychrometer recommended by the United States Weather Bureau for the measurements of barometric pressure, temperature, and relative humidity, respectively, were made use of in observing the corresponding weather quantities.

FIG. 2

In addition the various necessary voltmeters, ammeters, etc., as indicated in Fig. 5 were employed. One of the ammeters was used in the high-tension circuit. It was mounted on an insulator and its movement was shielded from electrostatic action by a tin-foil shield inside the case and attached to one terminal.

In addition to the above apparatus, we had for a while, the use of an oscillograph. Voltage curves were obtained by connecting the oscillograph to the *D* test coil in place of the voltmeter of Fig. 5.

The apparatus was all housed in a cheap building of corrugated iron, the outside of which is shown in Fig. 2.

The method of measurement employed was that devised by me and used at Telluride. In it the iron-loss of one transformer is balanced against the iron-loss of both transformers in such a manner that no iron-loss reading appears on the wattmeter, with the result that the wattmeter records only the losses in the high-voltage circuit of the transformer feeding the line. By this method of measurement the only correction which it is necessary to make in the wattmeter reading is to subtract from such reading the $I^2 R$ loss in the high-tension coil of the transformer feeding the line.

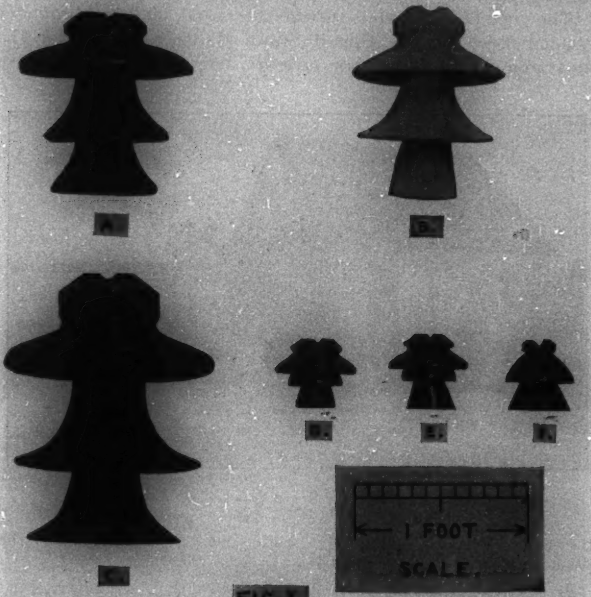


FIG. 3.

The diagram of connections is shown in Fig. 5. One of the transformers, designated as the "Power Transformer" is used to feed the line in the usual way; the other, designated as the "Balancing Transformer" is idle except as to its use for balancing purposes. As will be seen from the diagram each transformer has, in addition to its regular low-tension and high-tension windings, two auxiliary coils, designated as *C* test coil and *D* test coil; from the *D* test coil are brought off a number of leads. The voltmeter and the voltage circuit of the wattmeter are connected to the leads of the *D* test coil of the power transformer. The *D* test coil is so located as to give, as nearly as possible, a voltage reading which will be always proportional to the voltage across the high voltage terminals. In the case of the balancing transformer, the *D* test coil is idle. The *C* test coils of the two transformers are connected in series with a small auto transformer between them. With this method of connection, it will be apparent that, provided the auto-transformer does not have an appreciable voltage across its terminals, the magnetization wave of the balancing transformer will, if the iron of the two transformers is the same, be exactly identical with the magnetization wave of the power transformer; for, since the *C* test coil of both of the transformers is close to the iron, the voltage induced in the *C* test coil of the power transformer will be one dependent only upon the flux wave in the iron of this transformer, and will be independent of any reactions which there may be in any of the windings of the transformer. The result is that the *C* test coil of the

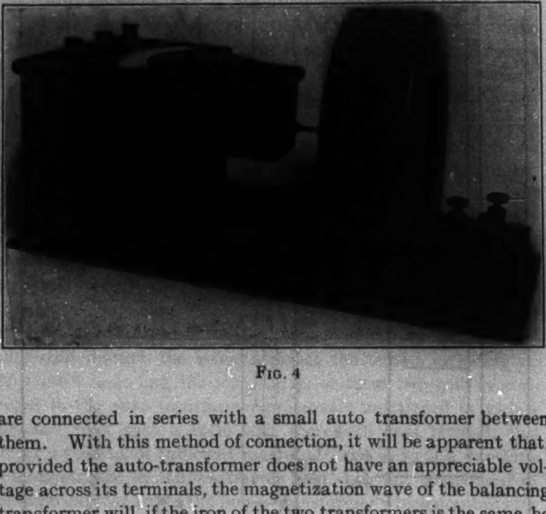
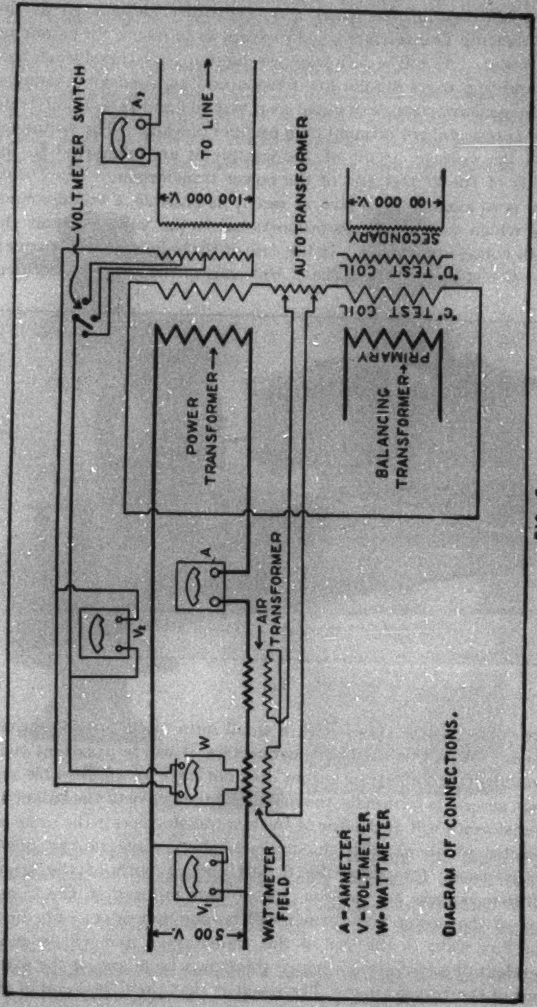


FIG. 4


VOLTMETER SWITCH
A1
TO LINE
100 000 V.
AUTOTRANSFORMER
100 000 V.
SECONDARY
'D' TEST COIL
'C' TEST COIL
PRIMARY
BALANCING TRANSFORMER
POWER TRANSFORMER
A
V2
AIR TRANSFORMER
W
WATTMETER FIELD
V1
500 V.

A = AMMETER
V - VOLTMETER
W - WATTMETER

DIAGRAM OF CONNECTIONS.

FIG. 5.

balancing transformer has impressed upon it a voltage exactly corresponding to the iron flux wave of the power transformer, and this condition will hold, no matter what load be put upon the power transformer. This being the case, it is evident that the current flowing in the circuit made up of the two *C* test coils and the auto transformer is proportional to and in step with that component of the main current, *i.e.*, the current supplied by the generator to the low voltage terminals of the power transformer, which corresponds to the iron loss of both transformers. Hence any current taken off of the auto transformer will be proportional to and in step with this iron loss component; and the value of the current in the secondary circuit of the auto transformer relative to the iron-loss component of the main current will depend upon the ratio of transformation employed in the auto-transformer, which ratio will hold through all ranges of voltage and all conditions of load on the power transformer.

As has been previously explained, and as is shown in the diagram, the field coil of the wattmeter is double. Through one of the windings of the wattmeter field coil and through one of the windings of the other coil mentioned above and designated in Fig. 5 as the " Air Transformer ", passes the main current to the low voltage winding of the power transformer. The other two windings, or secondaries, of the wattmeter field coil and the air transformer respectively, are connected in series, but in the reverse sense, so that the equal voltages induced in them oppose and neutralize each other. If the air transformer were not used, the voltage of the secondary of the wattmeter field coil would disturb the adjustment of the circuit including it. The circuit including the secondaries of these two coils is connected to the auto transformer previously mentioned in such a way and with such a ratio that there will pass through this circuit a current of sufficient magnitude and in such a direction as to neutralize in the wattmeter field coil that component of the main current fed to the power transformer which accounts for the iron loss in both transformers. It will be evident that by careful adjustment, not only may the wattmeter be made to read zero when there is no power delivered to the line from the power transformer, but also that it may be made to give no indication of the iron loss in the power transformer when the transformer is delivering power.

The other instruments and connections of Fig. 5 sufficiently explain themselves. The balancing transformer need not necessarily be a transformer, but may be a reactance, the iron of which has the same characteristics as that of the power transformer and which is worked at the same induction as the power transformer.

### RESULTS OF MEASUREMENTS

The endeavor was made to get some sort of a resistance for use on 100,000 volts, the value of which would remain practically constant, and which would not have a large charging current, so that by putting it across the terminals of the transformer, taking the wattmeter reading, and at the same time reading in the high voltage circuit the current taken by the resistance. the wattmeter reading might be checked by calculating the $C^2 R$ loss in the resistance. We were not successful, however, in finding any resistance which would answer for this purpose, and had to be content with the check readings described below.

In order to find out what effect, if any, the charging current of the line would have on this combination of wattmeters and transformers in the matter of producing errors in the reading, numerous sets of readings were taken of which the following are fair samples.

A measurement was taken on the experimental line. (The loss in this case is accompanied by a large charging current.) A reading was also taken on the dummy line. (In this case there is practically no charging current.) Then a reading was taken on the experimental line and the dummy line together. Assuming constancy of wave form, absolute accuracy would result in the sum of the separate readings being equal to the reading taken on the two lines together. The following is a typical set of readings, taken on the dummy line and an experimental line, consisting of 42,910 cm. 7-strand* aluminum cable, spaced at 55 in.

| Kilovolts | Exper. Line only (*A*) watts | Dummy Line only (*B*) watts | Dummy and Exp. Line | (*A*)+(*B*) | Error watts | Error per cent. |
|---|---|---|---|---|---|---|
| 80 | 138 | 54 | 200 | 102 | +17. | +8.13 |
| 70 | 92 | 39 | 140 | 131 | 9. | +6.43 |
| 60 | 64 | 25 | 97 | 89 | 8. | +8.24 |
| 70 | 102 | 40 | 152 | 151 | 1. | +0.66 |
| 70 | 106 | 42 | 158 | 148 | 10. | +6.33 |
| 70 | 104 | 39 | 158 | 143 | 15. | +9.5 |
|  |  |  | Average error = |  |  | +6.55 |

---

*Throughout this paper the word "strand" is understood to mean "wire," in accordance with common usage.

The above is considered very satisfactory. It must be remembered that the readings on the line are always more or less unsteady, due to the variation of line loss, especially if the measurement is taken above the critical point. This accounts for the considerable variation in the error. The average error, however, can be accounted for in another way. As will be seen later, the loss over the insulators is very sensitive to change of wave form, being greater for sharp wave forms. During the above set of measurements, the wave form was quite different when the experimental line was connected to the transformer from what it was when the experimental line was disconnected. The oscillograph curves in Fig. 6 (corresponding to 70 kilovolts) show this.

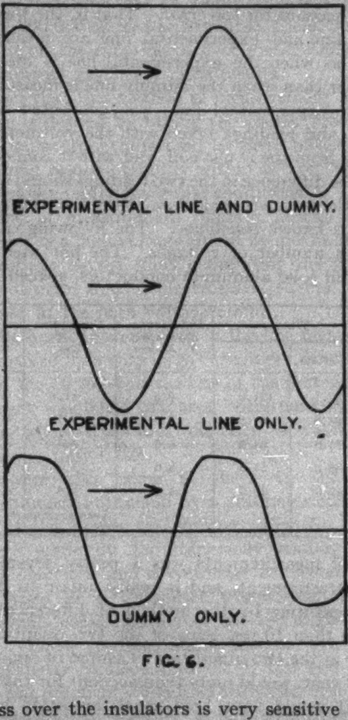


FIG. 6.

The first of them is the wave form with the experimental line and dummy line; the second is the wave form with the experimental line only; the third is the wave form with the dummy line only. There is no difference between the first and second because the wave form is controlled by the charging current and the dummy line has no measurable charging current. As will be seen, the distortion of the third wave form is in the direction to account for the error. That is, the wave form when the dummy line and experimental line are measured together is the same as when the experimental line is measured alone, and is sharper than when the dummy line is measured alone.

Again. the experimental line was connected to the power transformer, and readings taken with the voltmeter (see Fig. 5) disconnected from the *D* test coil, and with it connected to the *D* test coil. The difference in the two readings should be equal to the $C^2 R$ loss of the voltmeter calculated from the reading of the voltmeter and its known resistance. The following is a set of such readings at a number of voltages. The line used consisted of 51,529 cir. mil solid aluminum conductors, spaced at 84 in.

| Line kilovolts | Watts | | Difference = measured *V. M.* loss | Calculated *V. M.* loss | Error watts | Error per cent. |
|---|---|---|---|---|---|---|
| | *V. M.* on | *V. M.* off | | | | |
| 90 | 130.5 | 121.0 | 9.5 | 11.6 | +2.1 | +22.1 |
| 80 | 98.5 | 89.5 | 9.0 | 9.1 | + .1 | + 1.1 |
| 70 | 75.0 | 68.5 | 6.5 | 7.0 | + .5 | + 7.7 |
| 60 | 56.0 | 51.0 | 5.0 | 5.1 | + .1 | + 2.0 |
| 50 | 42.0 | 38.0 | 4.0 | 3.6 | — .4 | —10.0 |
| | | | | Average error | = | + 4.6 |

This set of measurements was a pretty severe test of the method of measurement, and is really unfair to it because we were here measuring by the method of differences, a quantity which is less than 10 per cent. of the two quantities involved, and an error in the two quantities measured of opposite sign and of only 1 per cent. would more than account for any of the errors obtained. It would have been much better to have had the voltmeter loss and the line loss approximately equal; the *D* test coil had not sufficient capacity for this. But, even leaving these facts out of consideration, the result is not bad. As in the previous case, the variation in the line loss probably accounts for the variation in the amounts of the errors, although to a less extent, inasmuch as the readings could be taken with the voltmeter on and off much more quickly than the changes could be made in the preceding case. It is to be noted that whereas the previous set of readings is only a relative check, the latter set furnishes not only a relative but an absolute check on the accuracy of the method of measurement, since the loss in the voltmeter was accurately known.

It may be added here that at Telluride, where a wire wound resistance of 1,000,000 ohms was available, check readings taken by means of it on the same method of measurement (but with different apparatus) gave very close results.

It is believed that this method of measurement may be made as accurate as is desired by taking the proper precautions, and that the particular apparatus used in these measurements was capable of giving results certainly within two or three per cent., and perhaps closer under favorable conditions.

This method of measurement offers a means of accurately measuring losses in a high voltage circuit by means of instruments in the low voltage circuit, thus eliminating the possibilities of danger, and of error due to electrostatic effects, when instruments are used in the high voltage circuit.

It should be borne in mind that in the line measurements the loss is accompanied by a very large charging current; for instance, in the case of the 60,000-volt reading of the first set of readings, the line current was 0.038 amperes, corresponding to 2280 apparent watts, whereas the loss was only 64 watts, so that the power factor was only 0.028.

Readings were also taken to check up the accuracy of voltage measurements obtained by a voltmeter connected to the *D* test coil of the power transformer (Fig. 5). These check readings were made by simultaneously reading a voltmeter connected as described and a voltmeter connected to the other transformer used as a voltmeter transformer with its high voltage terminals connected across the terminals of the power transformer. These readings show that the reading obtained from the voltmeter connected to the *D* test coil of the power transformer was practically identical with that obtained from the voltmeter transformer whether a line was connected to the power transformer or not.

As an example of the advantage of taking loss measurements by the method used instead of by reading power to the transformer with the line on, power to the transformer without the line, and taking the difference in the readings; and also to illustrate the efficacy of the air transformer, the three curves shown in Fig. 7 were obtained. One of these shows the result obtained by the subtraction method; one by the balancing method without the air transformer; and one by the method employed in this work. The errors in measurement obtained by the subtraction method are due not only to the fact that a difference is being measured and therefore the errors in the two measurements subtracted may be superposed, resulting in a considerable percentage of error in the quantity measured, but also to the fact that the charging current of the line produces more or less distortion in wave form, so that the wave form impressed upon the iron of the transformer when it is feeding the line is different from that when the line is disconnected. The result is that the iron loss on open circuit is not the same as the iron loss when the transformer is delivering current to the line, which greatly increases the subtraction error.

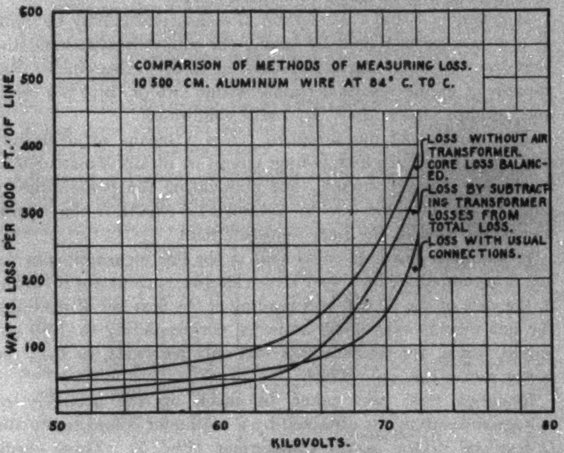


FIG. 7.

As has been mentioned previously, the measurements on the experimental line were at first made with the line supported on insulators. Measurements were taken in quick succession upon the dummy line and upon the experimental line. By subtracting the loss over the insulators on the dummy line from the total loss on the experimental line, a curve was obtained which, presumably, represented the atmospheric loss. This method of procedure was followed for sometime with apparently concordant results, but after a while very considerable discrepancies began to develop, and it was found that on different days widely differing results would be obtained. Finally, after a great deal of work, we concluded this was due to the variation in the losses over the insulators, brought about by varying weather conditions, and an endeavor was made to find some way of eliminating the insulator loss altogether. This was finally accomplished by suspending the line conductors from cords, the cords being attached to the insulators, which was found to be effective, so long as the cords remained dry and clean. The course finally adopted was that of using ordinary window cord boiled in paraffin for a few minutes, as the saturation with paraffin made the cord less liable to absorb moisture. The cords were frequently tested by placing them all in parallel across 100,000 volts (twice the voltage which they would ordinarily have, since on the line two of them would be in series) and measuring the loss upon them. If they were in good condition, the loss would not be more than three or four watts. If they were not in good condition, they would show a larger loss which would rapidly increase until they began to burn. Defective cords were always thrown away and replaced by new ones, with the result that the losses due to the cords were kept so low as to be altogether negligible.

The measurements with the line supported on insulators were carried on for about eight months before the discrepancies due to insulator losses became evident. The results obtained during this period were worthless and had to be discarded. The length of time which it took to discover these discrepancies and their cause was due, first, to the fact that so long as there were no considerable variations in weather conditions, the discrepancies were small and, secondly, because as the result of the work at Telluride and that done by Professor Ryan, it was thought that weather conditions, except precipitation, would make no difference in loss whether between line conductors, or over insulators, provided the voltage were left long enough on the line to bring the insulator loss to a steady condition.

As soon as the difficulty arising from the insulator loss had been eliminated, results began to be obtained which were more consistent, and it developed that, whereas, the work at Telluride seemed to show that weather conditions, except precipitation, would produce no difference in the loss, the weather conditions had, on the contrary, a great effect upon the loss. At first this result seemed to discredit either the measurements at Telluride or those at Niagara; but, when fuller data had been obtained at Niagara Falls, it was found, as explained later on, that the two results were perfectly concordant. An immense number of readings were taken on different size conductors at different spacings under various weather conditions. It was found that the losses varied considerably, but they seemed to be more affected by humidity conditions than anything else. Such variations in loss as there may have been, due to variations in barometric pressure, were not apparent. If they existed, they were masked by the variations due to humidity conditions. The variations in barometric pressure were small.

An endeavor was made to connect the loss and its variation directly with the relative humidity, but when the loss was plotted against the relative humidity it was not apparent that there was any definite law connecting them. A similar negative result was obtained by plotting loss against absolute humidity. The losses were then plotted against each of the various elements having to do with moisture in the atmosphere and also against combinations of these elements, with the idea of discovering whether any simple relation could be found. As the result of these trials it was found that if the loss were plotted against the product of vapor pressure by relative humidity, what appeared to be a definite relation was obtained. All the readings were then plotted in this way, and curves obtained for different size conductors and different distances between them. For convenience in reference, the product of the vapor pressure by relative humidity will be referred to as the " vapor product ".

In order to give an idea of the closeness with which the results followed the relation found, two of the many target diagrams from which the relation was obtained are shown in Figs. 8 and 9. It will be noted that in some cases the points lie quite close to the curve showing, apparently, a well defined law. In others, the points are more erratic. This is especially true for points obtained above the critical point or bend in the curve connecting loss and voltage (see Figs. 10 to 15 showing loss-voltage curves) because above the critical point, the loss is especially

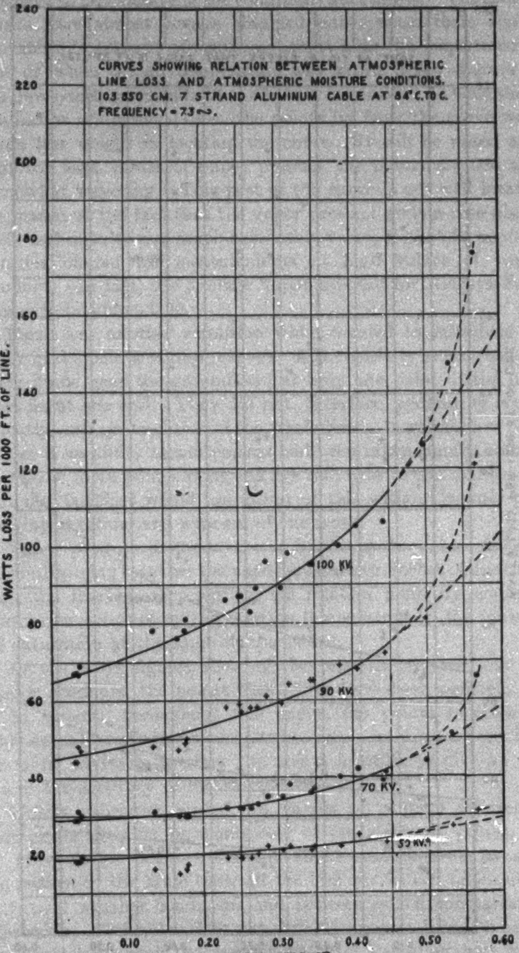

CURVES SHOWING RELATION BETWEEN ATMOSPHERIC LINE LOSS AND ATMOSPHERIC MOISTURE CONDITIONS.
103 850 CM. 7 STRAND ALUMINUM CABLE AT 84°C. TO C.
FREQUENCY = 73 ~.
WATTS LOSS PER 1000 FT. OF LINE.
240
220
200
180
160
140
120
100
80
60
40
20
100 KV.
90 KV.
70 KV.
50 KV.
0.10
0.20
0.30
0.40
0.50
0.60
VAPOR PRODUCT.

FIG. 8.

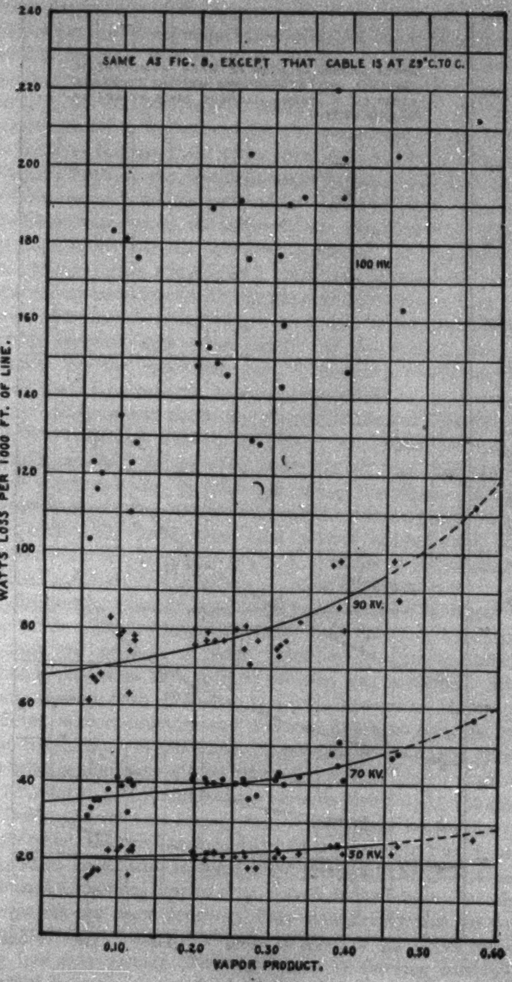

SAME AS FIG. 8, EXCEPT THAT CABLE IS AT 29°C. TO C.
WATTS LOSS PER 1000 FT. OF LINE.
240
220
200
180
160
140
120
100
80
60
40
20
100 KV.
90 KV.
70 KV.
50 KV.
0.10
0.20
0.30
0.40
0.50
0.60
VAPOR PRODUCT.

FIG. 9.

sensitive to any change in the conditions affecting it. The erratic points were almost always obtained either when there was a considerable amount of smoke apparent near the experimental line or when the air temperature was within a few degrees of the dew point, or when both conditions obtained. As both these conditions are unusual ones, the points far from the curve were given less weight in locating the curve. It will be noted also that for high values of vapor product the points are few and somewhat wavering. This part of the curve is not well located by reason of the fact that the vapor product seldom rose above 0.50, and usually was much below this value, so that few opportunities offered for measurements at high values of vapor product. In fact, the average vapor product for Niagara Falls seems to be about 0.20.

There was another condition which tended to introduce an error in the points of these curves. The humidity measurements were made near the ground and at only one point in the line; that is, at one end. They did not, therefore, necessarily represent the *average* condition of the whole line. It would have been better if humidity measurements had been taken simultaneously at two or more points along the line and near to the conductors, but our facilities would not admit of this without unduly prolonging the time and expense of the work.

Vapor product as made use of herein is the value obtained by multiplying together the vapor pressure (in inches of mercury) and the fraction representing the relative humidity (ratio of the vapor pressure at the existing temperature to the pressure of saturation at the same temperature).

In the other figures showing the relation between loss and vapor products, the points themselves have been omitted.

In general, throughout this paper, the points representing the actual readings are omitted, except in cases where it is thought advisable to show the points in order to give an idea as to the accuracy of measurements.

Unless otherwise stated, all values of voltage referred to herein are effective, or square root of mean square, values.

This relation between loss and vapor product is made use of to reduce to the same basis all the loss curves not taken under identical weather conditions and between which comparison is desirable. The value 0.20 was decided upon as being as nearly as could be judged the average value of vapor product which obtained at Niagara Falls, and the curves for comparison, except such as were taken under identical atmospheric conditions (in which case, in general, no correction is made) have been corrected to correspond to that value. On each of the curve sheets is noted either the fact that it has been so corrected, or else the atmospheric conditions under which the curves were actually taken.

As an example of the closeness with which the points fall upon the curves connecting loss and voltage, reference may be made to Figs. 14 and 22.

Figs. 10, 11, 12, 13, 14 and 15 are curves showing for different sizes of conductors, the variation in loss as the distance between the conductors is varied. In Fig. 14 is also shown the charging current for the 103,850 cir. mil conductor at the various distances.

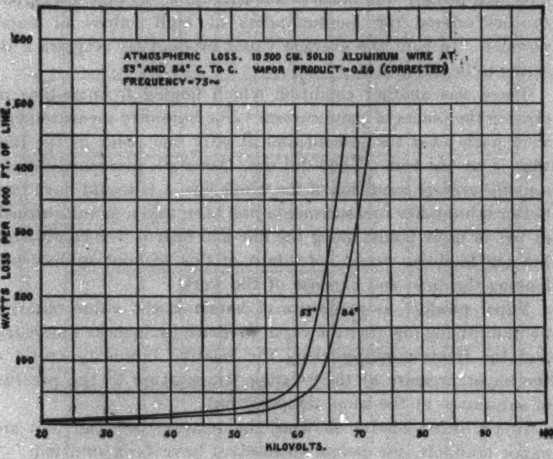


FIG. 10.

Fig. 16, 17 and 18 are curves showing the losses for different conductors at the same distances.

Figs. 19, 20 and 21 show the losses for conductors having approximately the same area of cross-section, but different strandings.

Fig. 22 shows the loss in conductors at different distances from the ground.

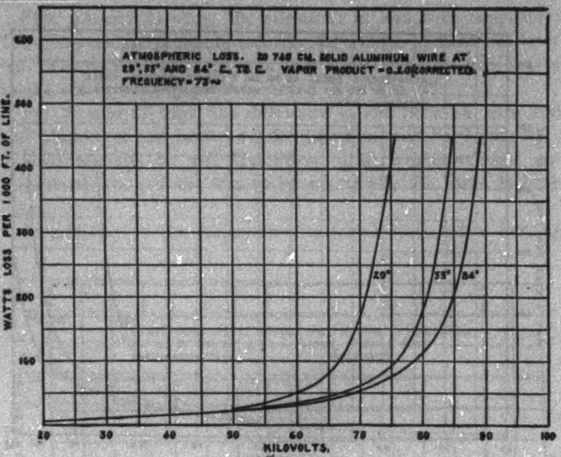

ATMOSPHERIC LOSS. 20 740 CM. SOLID ALUMINUM WIRE AT
29°, 55° AND 84° C. TO C. VAPOR PRODUCT = 0.20 (CORRECTED)
FREQUENCY = 73 ~
WATTS LOSS PER 1000 FT. OF LINE.
600
500
400
300
200
100
29°
55°
84°
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 11.

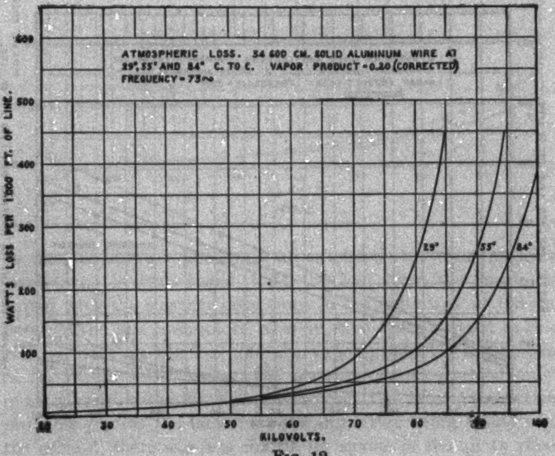

ATMOSPHERIC LOSS. 34 600 CM. SOLID ALUMINUM WIRE AT
29°, 55° AND 84° C. TO C. VAPOR PRODUCT = 0.20 (CORRECTED)
FREQUENCY = 73 ~
WATTS LOSS PER 1000 FT. OF LINE.
600
500
400
300
200
100
29°
55°
84°
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 12

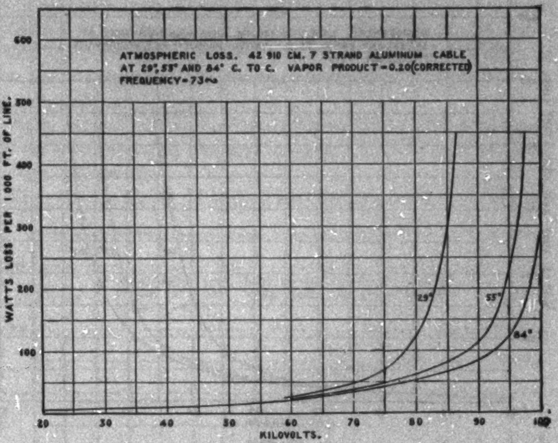

ATMOSPHERIC LOSS. 42 910 CM. 7 STRAND ALUMINUM CABLE
AT 29°, 55° AND 84° C. TO C. VAPOR PRODUCT - 0.20 (CORRECTED)
FREQUENCY - 73 ~
WATTS LOSS PER 1 000 FT. OF LINE.
600
500
400
300
200
100
20
30
40
50
60
70
80
90
100
KILOVOLTS.
29°
55°
84°

FIG. 13.

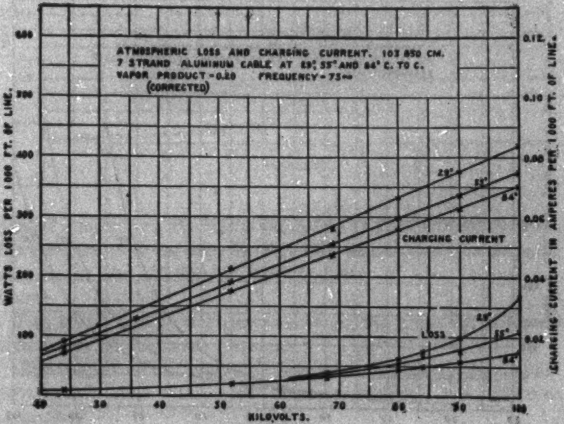

ATMOSPHERIC LOSS AND CHARGING CURRENT. 103 850 CM.
7 STRAND ALUMINUM CABLE AT 29°, 55° AND 84° C. TO C.
VAPOR PRODUCT - 0.20 FREQUENCY - 73 ~
(CORRECTED)
WATTS LOSS PER 1 000 FT. OF LINE.
CHARGING CURRENT IN AMPERES PER 1 000 FT. OF LINE.
600
500
400
300
200
100
0.12
0.10
0.08
0.06
0.04
0.02
20
30
40
50
60
70
80
90
100
KILOVOLTS.
29°
55°
84°
CHARGING CURRENT
LOSS
29°
55°
84°

FIG. 14.

Figs. 23 and 24 show the variation in loss with frequency. These curves are probably in error, as will be pointed out later on. The oscillograph curves in Fig. 25 show the voltage waves at the corresponding points marked *X* in Fig. 23.

Fig. 26 and 27 show the difference in loss between hard and soft aluminum and between soft aluminum and hard copper.

Measurements on soft aluminum cable, weathered and unweathered, showed the loss to be practically the same in both cases.

In addition to the measurements which were taken bearing

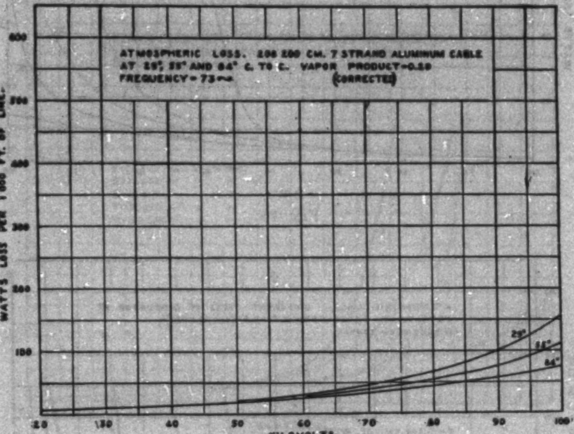


FIG. 13.

on the loss between line wires, an extended study was made on insulators. It was found that the loss over the insulators varied with the weather conditions in the same way as the loss between the line conductors, namely, that there seemed to be a relation between the loss and the vapor product. In the case of the insulators, however, the measurements coincided much more closely with the line embodying the law of variation, probably due to the fact that, the insulators being tested near the ground, there was less chance for smoke in the air to affect them than in the case of the cables some distance above the

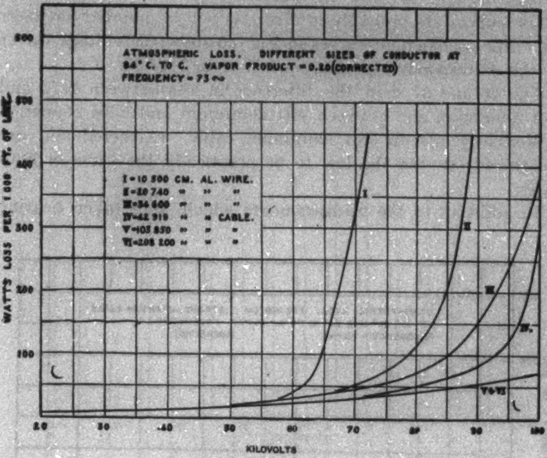

ATMOSPHERIC LOSS. DIFFERENT SIZES OF CONDUCTOR AT
24° C. TO C. VAPOR PRODUCT = 0.20 (CORRECTED)
FREQUENCY = 73 ~
I = 10 500 CM. AL. WIRE.
II = 20 740 " " "
III = 34 600 " " "
IV = 42 910 " " CABLE.
V = 103 850 " " "
VI = 208 200 " " "
I
II
III
IV.
V & VI
WATTS LOSS PER 1000 FT. OF LINE.
100
200
300
400
500
600
20
30
40
50
60
70
80
90
100
KILOVOLTS

FIG. 16

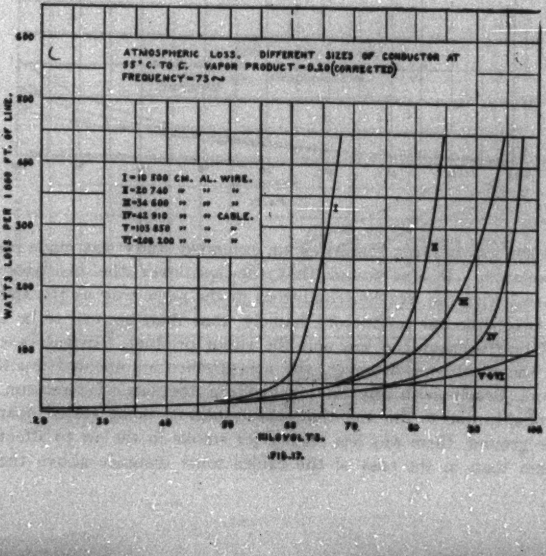

ATMOSPHERIC LOSS. DIFFERENT SIZES OF CONDUCTOR AT
35° C. TO C. VAPOR PRODUCT = 0.20 (CORRECTED)
FREQUENCY = 73 ~
I = 10 500 CM. AL. WIRE.
II = 20 740 " " "
III = 34 600 " " "
IV = 42 910 " " CABLE.
V = 103 850 " " "
VI = 208 200 " " "
I
II
III
IV
V & VI
WATTS LOSS PER 1000 FT. OF LINE.
100
200
300
400
500
600
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 17.

ground. This was also due possibly to the fact that the humidity measurements were made beside the insulators, whereas, as previously mentioned, the humidity measurements for the line were made only at one end of the line and near the ground instead of near the line cables. When voltage was first applied to the insulators, the loss was irregular and it was necessary to keep voltage impressed upon them for sometime until the loss steadied down and an accurate reading could be taken. The readings were all taken on five insulators in parallel, the voltage being applied between the necks of the insulators and the metal pins, although the curves are plotted for the loss over a single insulator. The curves connecting loss over insulators and vapor product are not carried above a value of the latter quantity equal to 0.20 for the reason that readings could not be obtained above this point without the expenditure of a great deal of time.

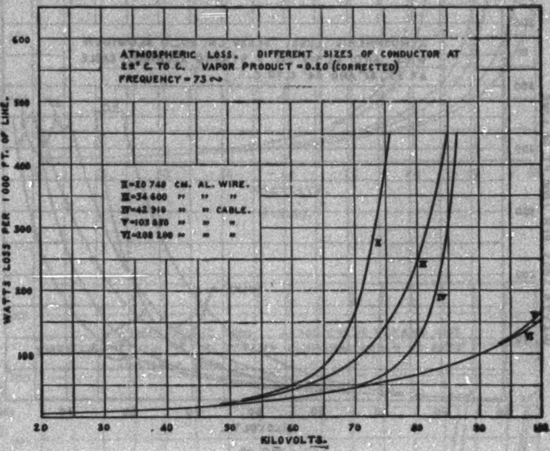


FIG. 18

Figs. 28 and 29 show for the various insulators, *A*, *B*, and *C*, the relation between the loss and the vapor product. Fig. 28 is a target diagram showing all the points on the curves. In Fig. 29, the points have been omitted. The insulators are designated by letters which correspond to those of the dimension photographs of the insulators previously given in Fig. 3.

The losses over insulators of different sizes were quite different, as is shown by Fig. 30. These go only to 50 kilovolts as it was not safe to go higher on the smaller insulators.

Fig. 31 shows the loss over the larger insulators, up to 100 kilovolts, when there was fog and drizzling rain, as compared with the loss under ordinary conditions.

Fig. 32 shows the loss over an insulator with a metal pin, over the same insulator with a metal pin and a metal plate in contact with the lower petticoat of the insulator, and over the insulator with the metal plate but without the pin, the various arrangements of the insulator being shown in Fig. 33. It will be noted from these loss curves that while the losses over the insulator with the metal pin only and with the metal pin and plate were the same, the loss over the insulator with the metal plate only was considerably less than in the other two cases. This curve was taken as having a bearing on the loss over different size insulators, as will be explained later.

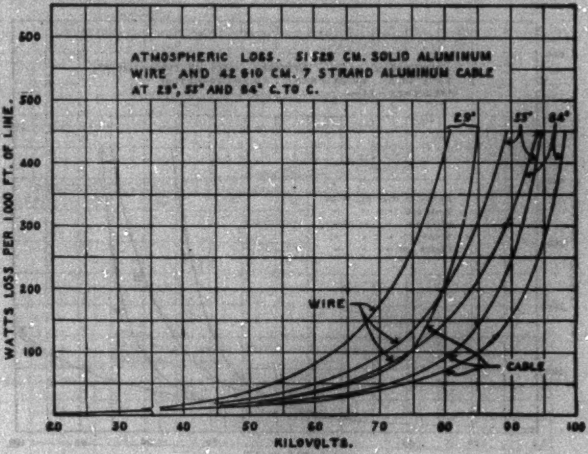


FIG. 18

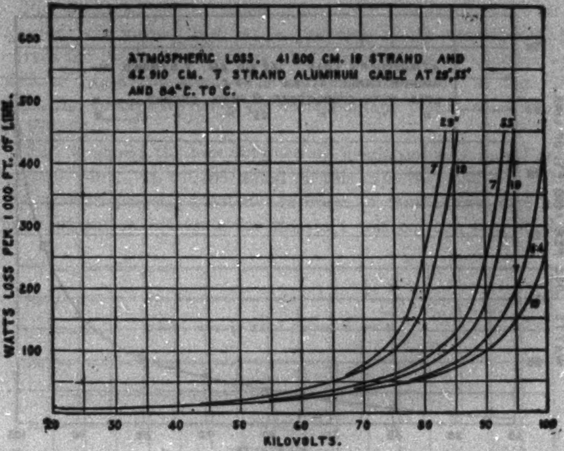

ATMOSPHERIC LOSS. 41 800 CM. 19 STRAND AND
42 910 CM. 7 STRAND ALUMINUM CABLE AT 29°, 55°
AND 84° C. TO C.
WATTS LOSS PER 1 000 FT. OF LINE.
100
200
300
400
500
600
20
30
40
50
60
70
80
90
100
KILOVOLTS.
29°
55°
84°
7
19
7
19
7
19

FIG. 20.

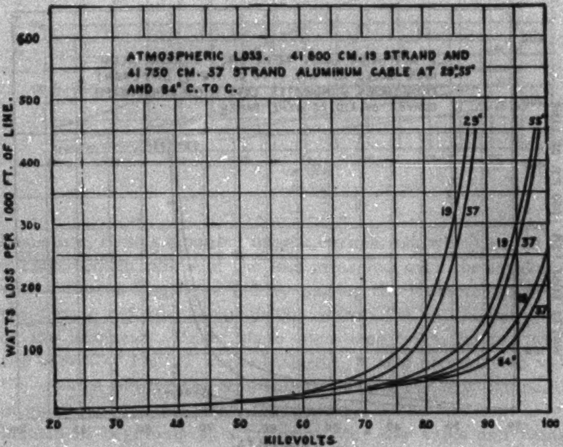

ATMOSPHERIC LOSS. 41 800 CM. 19 STRAND AND
41 750 CM. 37 STRAND ALUMINUM CABLE AT 29°, 55°
AND 84° C. TO C.
WATTS LOSS PER 1 000 FT. OF LINE.
100
200
300
400
500
600
20
30
40
50
60
70
80
90
100
KILOVOLTS
29°
55°
84°
19
37
19
37
19
37

FIG. 21.

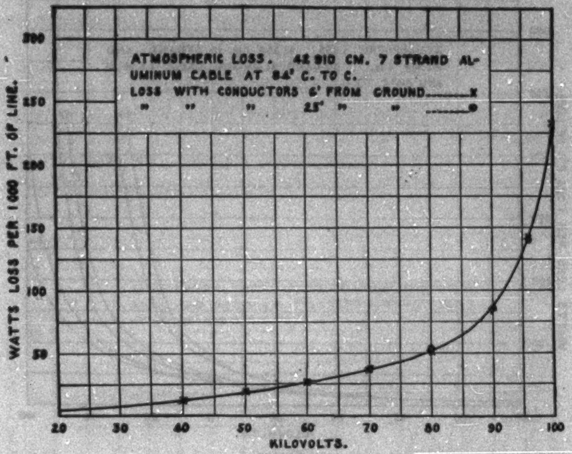

ATMOSPHERIC LOSS. 42 910 CM. 7 STRAND ALUMINUM CABLE AT 84' C. TO C.
LOSS WITH CONDUCTORS 6' FROM GROUND ——x
" " " 25' " " ——●
WATTS LOSS PER 1000 FT. OF LINE.
300
250
200
150
100
50
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 22.

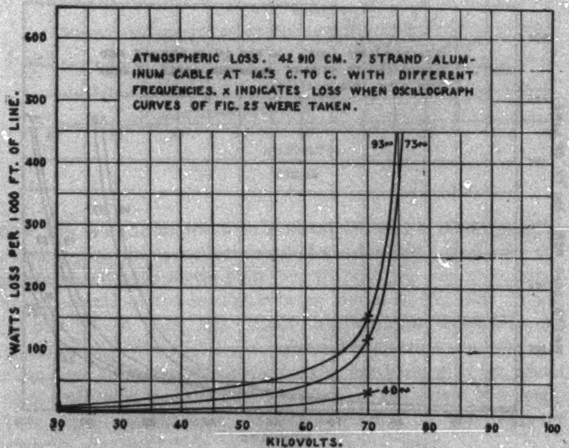

ATMOSPHERIC LOSS. 42 910 CM. 7 STRAND ALUMINUM CABLE AT 14'.5 C. TO C. WITH DIFFERENT FREQUENCIES. x INDICATES LOSS WHEN OSCILLOGRAPH CURVES OF FIG. 25 WERE TAKEN.
93~
73~
40~
WATTS LOSS PER 1000 FT. OF LINE.
600
500
400
300
200
100
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 23.

Fig. 34 shows the variation in loss over insulators as the frequency was varied, but, as in the case of the corresponding curves for the line conductors, this curve is open to question as will be explained later. The oscillograph curves in Fig. 35 show the voltage waves of the corresponding points, marked $X$, of Fig. 34.

Fig. 36 shows the loss obtained on insulators with metal and wooden pins. It will be noted in this case that the loss with the wooden pin was greater. In order to demonstrate whether an explanation hit upon for this fact was correct, one of the insulators, $B$, was mounted upon a curtain rod, which served as a long wooden pin, and the loss measured over the insulator with different lengths of pin by placing the lower terminal on the curtain rod at different distances from the bottom petticoat of the insulator. Under these conditions, with the rod wet, the curves of Fig. 37 were obtained. It was necessary to wet the wooden pin for the reason that when it was dry, the point of maximum loss fell inside the insulator, so that the loss curve, instead of beginning at a comparatively low value and rising to a maximum and then falling off again, continually fell off

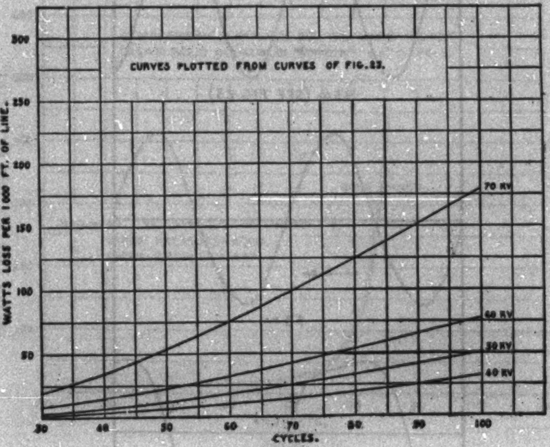


FIG. 24.

as the length of the pin was increased. An explanation of this will be given later.

An endeavor was made to measure the loss over insulators when it was raining, but the loss was so variable, due to variation in the rate of precipitation and gusts of wind, that no satisfactory curve could be obtained. It was determined, however, that the loss with a hard rain was less than in the case of fog and drizzling rain, the curve for which is shown in Fig. 31. The loss over insulators with hoar frost upon them was also less than with fog.

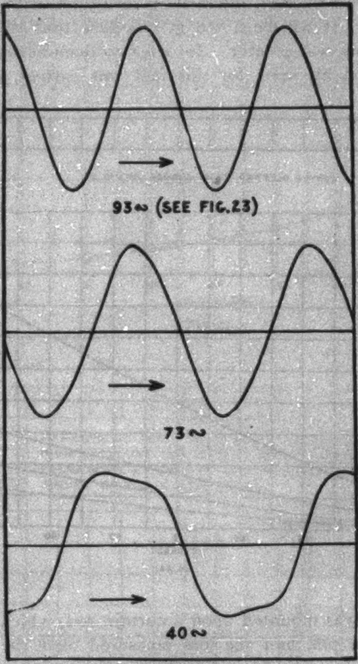


FIG. 25.

Tests were made on an insulator with increasing and decreasing voltage to see whether or not this made any difference in the loss obtained. It was found that if a high voltage were first applied to the insulator there was no difference in the loss curve with ascending and descending voltage.

Measurements were made on a set of insulators, the metal pins of which were not cemented in the insulators, and on another set, the metal pins of which were cemented, to see if any difference would be found. As long as the cement was wet, there was a difference, but after the cement had set and become dry, there was no difference. This being the case, all the subsequent tests were made with the pins uncemented.

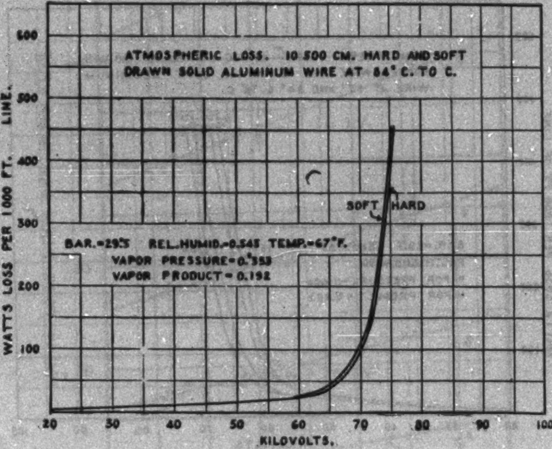


FIG. 26.

A number of readings were taken on broken insulators. These readings were taken by first obtaining a loss reading on the insulator intact, and then gradually breaking the petticoats off, beginning with the inner one. The loss had not materially changed with the two inner petticoats broken away, and the upper petticoat still intact, but immediately ran up when the upper petticoat was broken. These measurements were all made on dry insulators.

## Discussion of Results

At Telluride, the measurements were all taken on lines carried upon insulators; measurements were also made on a dummy line having the same number of insulators and cross-arms as the main line, and the atmospheric losses arrived at by subtraction. By this method concordant results were obtained, although such method of measurement did not produce satisfactory results at Niagara. The probable reason for this will be explained later on. The Telluride results apparently demonstrated certain facts and justified certain conclusions which were brought out in my report on the Telluride work. As the result of the Niagara work, some of these conclusions have had to be abandoned. In order properly to discuss the subject, it is thought advisable to enumerate here the conclusions arrived at as the result of the Telluride work. They are as follows:

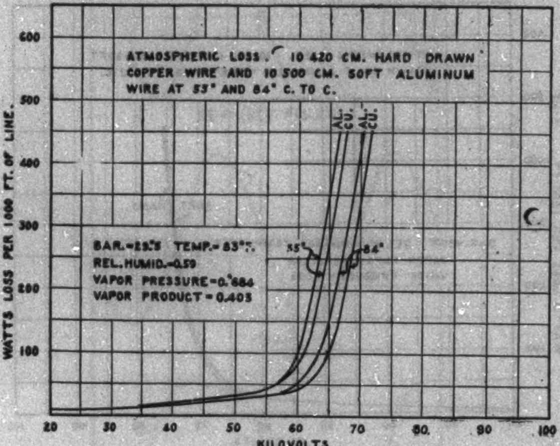


FIG. 27.

(*a.*) That there is a certain critical point in the curve connecting loss and voltage at which the loss begins to increase very rapidly.

(*b.*) That the loss below the critical point is made up entirely of loss over the insulators; and that the loss above the critical point is made up of insulator loss plus a loss through the atmosphere.

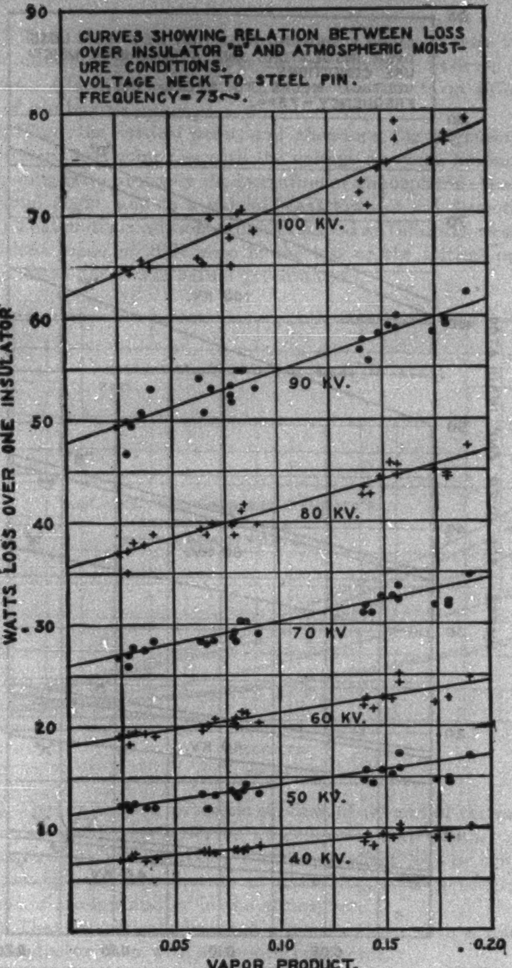

CURVES SHOWING RELATION BETWEEN LOSS OVER INSULATOR "B" AND ATMOSPHERIC MOISTURE CONDITIONS.
VOLTAGE NECK TO STEEL PIN.
FREQUENCY = 75~.
WATTS LOSS OVER ONE INSULATOR
90
80
70
60
50
40
30
20
10
100 KV.
90 KV.
80 KV.
70 KV
60 KV.
50 KV.
40 KV.
0.05
0.10
0.15
0.20
VAPOR PRODUCT.

FIG. 28.

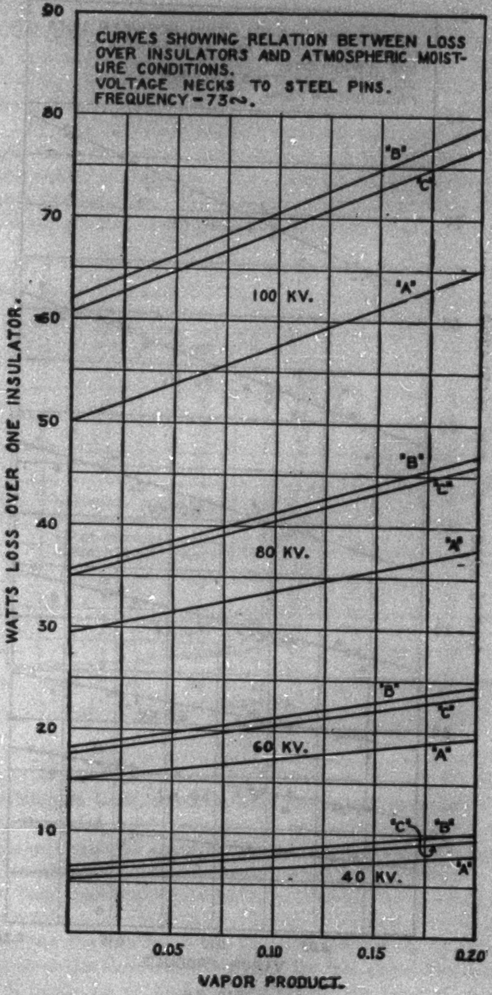

CURVES SHOWING RELATION BETWEEN LOSS OVER INSULATORS AND ATMOSPHERIC MOISTURE CONDITIONS.
VOLTAGE NECKS TO STEEL PINS.
FREQUENCY - 73 ~.
WATTS LOSS OVER ONE INSULATOR.
90
80
70
60
50
40
30
20
10
"B"
"C"
"A"
100 KV.
"B"
"C"
"A"
80 KV.
"B"
"C"
"A"
60 KV.
"C"
"B"
"A"
40 KV.
0.05
0.10
0.15
0.20
VAPOR PRODUCT.

FIG. 29.

(*c.*) That the critical point depends upon the maximum value of the electromotive force wave and the distance between conductors. (Facilities were lacking for measurements on different sizes of conductors.)

(*d.*) That the critical point, and therefore, the beginning of atmospheric loss coincides with the voltage at which luminosity and hissing (also probably the formation of atmospheric chemical products) begin, and to a partial breakdown of the dielectric.*

(*e.*) That under conditions which obtained at Telluride, weather conditions made no difference in the loss or the critical point, except when there was actual precipitation.

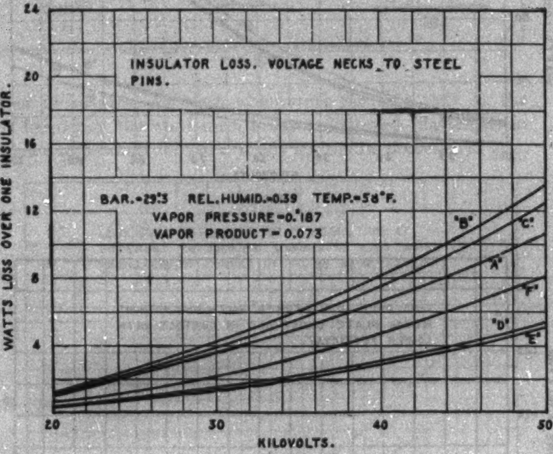


FIG. 30.

(*f.*) That it seemed probable in view of (*e*) and of the range of weather conditions observed at Telluride, that weather conditions (except precipitation) would not affect loss or critical point, except perhaps in case of dense fog, or a considerable amount of foreign matter in the atmosphere.

(*g.*) That the critical point is at a lower voltage with a roughened conductor than with a smooth conductor.

---

*Professor Ryan gives Mr. Scott credit for this observation, but it was first brought out in my Telluride report, as reference to Mr. Scott's paper will show.

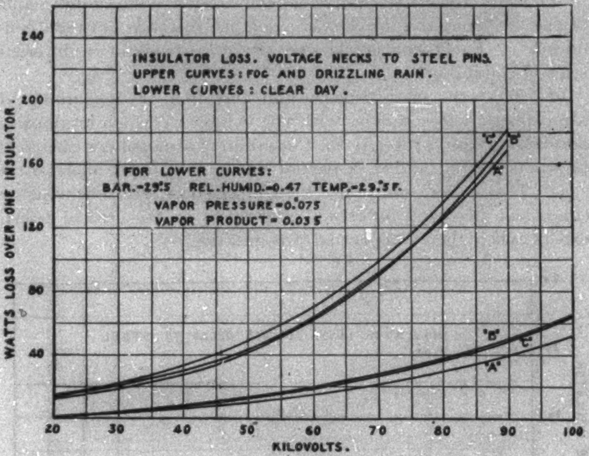

INSULATOR LOSS. VOLTAGE NECKS TO STEEL PINS.
UPPER CURVES: FOG AND DRIZZLING RAIN.
LOWER CURVES: CLEAR DAY.
FOR LOWER CURVES:
BAR.-29.5 REL. HUMID.-0.47 TEMP.-29.5 F.
VAPOR PRESSURE-0.075
VAPOR PRODUCT-0.035
'C'
'B'
'A'
'B'
'C'
'A'
WATTS LOSS OVER ONE INSULATOR.
240
200
160
120
80
40
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 31.

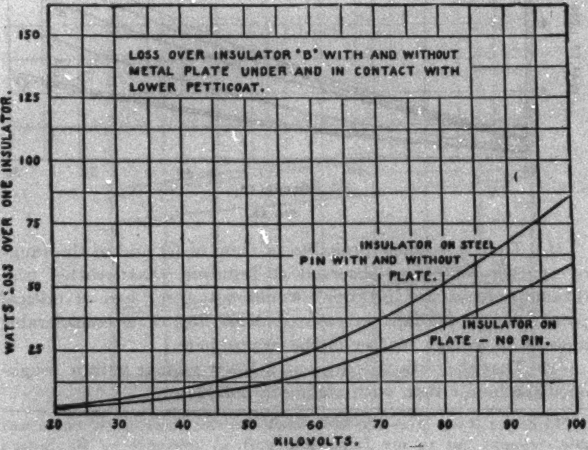

LOSS OVER INSULATOR 'B' WITH AND WITHOUT METAL PLATE UNDER AND IN CONTACT WITH LOWER PETTICOAT.
INSULATOR ON STEEL PIN WITH AND WITHOUT PLATE.
INSULATOR ON PLATE — NO PIN.
WATTS LOSS OVER ONE INSULATOR.
150
125
100
75
50
25
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 32.

(*h.*) Measurements taken at different frequencies showed that the losses were lower and the critical point higher at the lower frequencies, but these results were viewed with suspicion for a number of reasons, amongst which was the fact that at the lower frequency the wave-form became distorted (flattened) in a manner to account for part, if not all, of the decrease in loss.

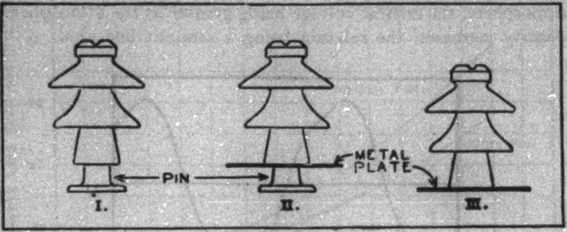


FIG. 33.

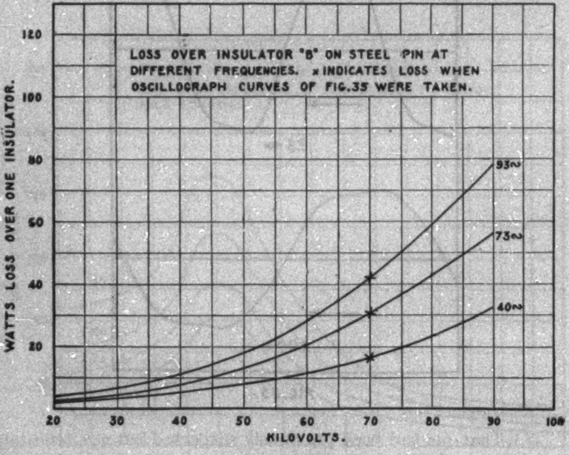


FIG. 34.

Professor Ryan's results, obtained subsequently, confirmed (*a*), (*b*), (*c*), and (*d*). They also confirmed (*f*) so far as it relates to the presence of water vapor, but not so far as it relates to the barometric pressure and temperature. In addition, as the result of his measurements, he arrived at the following conclusions.

(*i.*) That the critical point depends upon the density of the atmosphere, the critical voltage being greater as the atmospheric density increases, the relation being a straight line one.

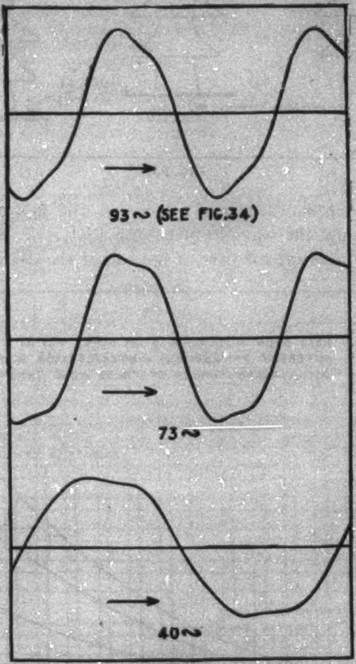


FIG. 35.

(*j.*) That (as had been previously suspected but not definitely known) the critical voltage depends upon the rate of fall of potential, or dielectric stress, near the conductor; that is, for a given atmospheric density, the partial or local breakdown of the dielectric occurs when a certain local rate of fall of potential or dielectric stress, has been reached.

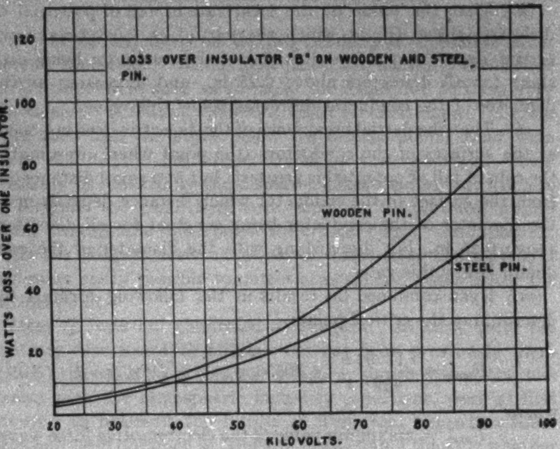

LOSS OVER INSULATOR "B" ON WOODEN AND STEEL PIN.
WATTS LOSS OVER ONE INSULATOR.
120
100
80
60
40
20
WOODEN PIN.
STEEL PIN.
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 36.

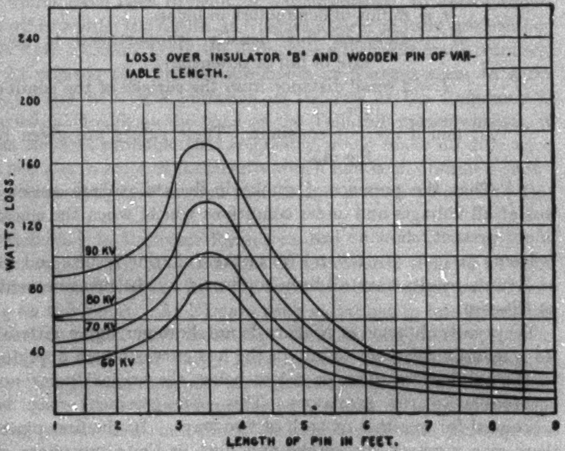

LOSS OVER INSULATOR "B" AND WOODEN PIN OF VARIABLE LENGTH.
WATTS LOSS.
240
200
160
120
80
40
90 KV
80 KV
70 KV
60 KV
1
2
3
4
5
6
7
8
9
LENGTH OF PIN IN FEET.

FIG. 37.

(*k.*) That the value of the local rate of fall of potential or dielectric stress, $D'$, at which the partial or local breakdown occurs, depends upon the diameter of the conductor being constant for all diameters above 0.25 in., and increasing as the diameter of the conductor decreases below this value.

(*l.*) That the partial breakdown of the dielectric does not occur at the surfaces of the conductors (the point where presumably the rate of fall of potential is greatest) but at a small distance ($d$) from the surface of the conductor which distance depends upon the diameter of the conductor being constant for all diameters above 0.25 in., but diminishing with the diameter of the conductor below this value.

(*m.*) Ryan combined his results in the following formula for determining the critical point:

$$E_{max} = \frac{17.94\, b}{459 + t} \times 2055 \log_{10} \frac{s}{r} \times D' \times (r + d) \times 10^{10}$$

where

$E_{max}$ = maximum value of the electromotive force wave.
$b$ = barometer in inches.
$t$ = temperature in degrees fahrenheit.
$s$ = distance between centers of conductors in inches.
$r$ = radius of conductors in inches.
$D'$ = dielectric flux density (proportional to local rate of fall of potential).
$d$ = a small distance from the surface of the conductor.
$D'$ and $d$ are not constant. Their values are given by Fig. 45.

(*n.*) That the presence of smoke in the atmosphere causes a loss at all voltages and under conditions which, when the smoke is not present, show no loss.

Items (*a*), (*c*), (*d*), (*e*) and (*g*) of the Telluride results and (*n*) of Ryan's results have all been confirmed by the measurements at Niagara.

The results obtained at Niagara do not, however, agree with (*b*). As is seen by reference to any of the loss curves herein applying to the conductors, there is a loss below the critical point not chargeable to the insulators. This non-agreement may be accounted for in either or both of two ways. In the first place, there was more or less smoke and dust in the atmosphere at Niagara, whereas the atmosphere at Telluride was probably as nearly absolutely free from floating particles as is possible under natural conditions. In the next place, the humidity conditions at Telluride were such as to make the losses due to them very low indeed. It follows, therefore, that the conditions at Telluride were such that the losses below the critical point, other than those due to the insulators, would be very low, and would probably be masked by the insulator losses themselves; whereas at Niagara the conditions were such as to produce appreciable atmospheric losses below the critical point. And, besides, as in the Niagara tests all insulator losses were eliminated, it was more easily possible to detect atmospheric losses below the critical point.

Item (*f*) was not confirmed at Niagara. In fact, quite the contrary was found to obtain. As has been previously mentioned, the results obtained at Niagara, showing that the loss varied with the atmospheric humidity conditions, were at first thought to discredit the results at Telluride, but when fuller data had been obtained at Niagara, it was found that the weather conditions (and the variations of them) which obtained at Telluride would produce so small a variation in the losses that it would have been difficult, if not impossible, to detect them. In other words, the results at Niagara appear to fully confirm (*e*), but were contrary to (*f*), the deduction which was made from (*e*).

As regards (*h*), the measurements at Niagara seem to show that there will be a variation in the loss as the frequency is varied, although at the time of the Telluride measurements, it was thought probable that frequency would make no difference in the loss in spite of the results which had been obtained showing apparently a variation of loss and critical point with frequency.

Referring to Professor Ryan's results:

As regards (*i*), the variations in atmospheric density at both Telluride and Niagara were too slight to obtain any results bearing on this point. At Niagara such variations in loss or critical point as might have been due to variations in atmospheric density would have easily been masked by variations due to other conditions, especially moisture conditions. The barometer was never lower than 29 in. nor higher than 30 in., the average being about 29.5 in. Since the density of the atmosphere varies as the absolute temperature, the variation in density due to temperature would be comparatively small.

As regards (*j*) *k*), (*l*) and (*m*), the results both at Telluride and Niagara show that there is a relation between distance between conductors and the critical point, and the latter measurements show that there is also a relation between diameters of conductors and the critical point. Both these would have a bearing upon the local rate of fall of potential, or dielectric stress. The results obtained at Niagara do not, however, bear out quantitatively those obtained by Ryan. Neither do they seem to bear out his results, qualitatively, as the diameter of the conductor is varied, though they do seem to agree, qualitatively, with his results for variation of critical point as the distance between conductors is varied.

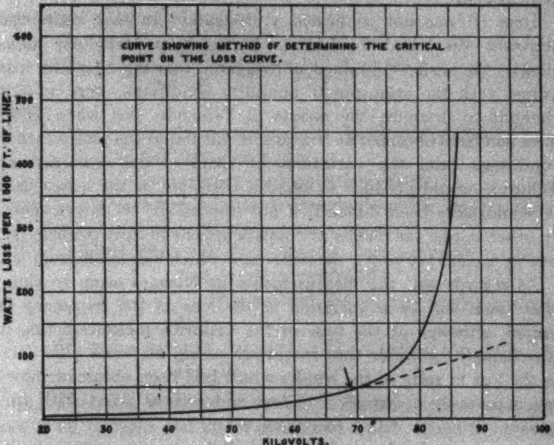


FIG. 38.

A number of the above points are more fully borne upon by what follows:

In Fig. 38 is shown the method of determining the critical point. The lower limb of the loss curve is extended in accordance with what, so far as can be judged, is the law of the lower portion of the curve and the critical point taken as the point where the upper limb leaves the lower limb prolonged. Some writers have determined the critical point by extending the upper limb of the curve down to the horizontal axis. Such course is clearly incorrect.

Fig. 14 shows not only the loss curves for a given conductor at different spacings, but also the corresponding charging current curves. The charging current curves are included mainly to show that there is no change in the charging current due to the critical point. As will be seen from Fig. 14, the line charging current curves are straight lines, and in all the measurements I have ever taken this has been the case, so long as the electromotive force wave has not been distorted. Further, this straight line relation has always held even when the voltage was pushed to a value which took the loss curve very considerably above the critical point.

Figs. 19, 20 and 21 show the comparison of the loss curves of solid and stranded conductors, and of stranded conductors with different numbers of strands. Fig. 19 clearly shows that for a stranded conductor of given circular mil section, the loss is less and the critical point higher than for the corresponding solid conductor. The two conductors compared in this case have not the same circular mil section, the area of the stranded conductor being less than that of the solid conductor; but, even with this disadvantage, the stranded conductor shows a considerable advantage over the solid. Fig. 20 shows a comparison between a 19 strand cable and a 7 strand cable; while Fig. 21 shows a comparison between a 19 strand cable and a 37 strand cable. It is clear from these three curves that not only is a stranded conductor superior to a solid one, so far as loss and critical point are concerned; but, also, that the finer the strands of the stranded conductor, the better, so far as the critical point is concerned. That is to say, the effective diameter of the stranded conductor is greater than for the corresponding solid conductor, and for a given conductive area of cross-section, the greater the number of strands in the stranded conductor, the greater is its effective diameter so far as critical point and loss are concerned. Of course, it is perfectly evident that the actual outside diameter of a stranded conductor is greater than that of the corresponding solid conductor, but there has been some question, heretofore, as to whether the increase of physical diameter would not be offset by the fact that the surface of the stranded conductor is corrugated. These curves, apparently, settle this matter to the effect that the increase of diameter more than offsets any ill effects due to corrugations. As a matter of fact, as will be shown later on, the stranding seems not only to offset the effect of the corrugations but, when the stranding is fine enough, to more than offset them and make the effective diameter of a stranded conductor greater than that of a solid conductor having a diameter equal to the outside diameter of the stranded conductor.

Fig. 22 shows two loss curves, one with conductors 25 feet from the ground and the other with conductors 6 feet from the ground; the size and spacing of the conductors being the same in the two cases. These measurements were taken to determine whether variation in the distance from the earth had any effect on the loss or critical point. They show that such variation has apparently no effect.

Fig. 23 shows measurements taken on a pair of conductors at different frequencies. Apparently the loss changes with the frequency, but the extent of this change as shown by the figure is open to question, as will be seen on referring to Fig. 25 which shows the wave forms corresponding to the 70 kilovolt points of the curves of Fig. 23. The waves for the 93-cycle curve and for the 73-cycle curve are practically identical, but that for the 40-cycle curve is considerably flattened. The 40-cycle loss curve is, therefore, undoubtedly a great deal lower than it would be if the wave form had not been distorted so that the result obtained for 40 cycles is not comparable to those obtained for 73 cycles and 93 cycles respectively. The curves for the latter two frequencies are, however, comparable and seem to show that the loss is less the lower the frequency. I hope, later on, to obtain measurements at different frequencies under conditions which will obviate distortion of the wave form.

Similar remarks will apply to the variation of insulator loss with frequency as shown in Fig. 34, to which Fig. 35, showing the wave forms, applies. Apparently, there is a decrease in insulator loss with frequency, but it is evident that if the wave form were not distorted, the change in loss with frequency would not be as great as is shown by Fig. 34.

Fig. 24 is derived from Fig. 23. In viewing this figure what has been said in regard to distortion of wave form should be borne in mind. It seems evident that if the wave form were not distorted at 40 cycles, the curves shown in Fig. 24 would be higher at the lower frequencies than there shown.

A reference to Figs. 26 and 27 shows that hard drawn wire is somewhat superior to soft drawn wire, because of its smoother surface, but that the difference is not great. These figures, also, show that there is practically no difference between copper and aluminum wire in the matter of loss and critical point. There may be mentioned in this connection a point which has already been referred to, that there is no difference between weathered and unweathered wire as regards loss and critical point.

The results obtained in measuring losses with insulators on wooden and steel pins, as shown by Fig. 36, were rather a surprise. On thinking the matter over, I came to the conclusion that this effect is due to the fact that a large part of the current taken by the insulator is charging current; that is, a current in quadrature with the electromotive force, and that mounting the insulator on a wooden pin is equivalent to inserting a resistance in series with a condenser. As is well known, the value of such a resistance can be considerable, before the voltage impressed upon the condenser is materially reduced, because of the fact that the voltages taken by the resistance and the condenser, respectively, are in quadrature. This being the case, it would be possible to have a considerable resistance, and therefore loss, in the pin, without materially reducing the current taken by the insulator. This would mean considerably more insulator loss with a wooden pin than with a steel pin. In order to test this out, the measurements of Fig. 37 were taken, showing the relation between the loss and the length of the wooden insulator pin. These curves clearly show the correctness of the above explanation since, in the case of a resistance and a capacity in series and a constant voltage impressed upon the combination, the loss would increase as the resistance is increased up to a certain maximum and would thereafter decrease. These measurements go a long way towards explaining some of the difficulties experienced in the burning and deterioration of wooden pins.

In order to get some further light on this matter of charging current in the insulators, the measurements of Fig. 32 were taken. The conditions under which these measurements were taken are shown in Fig. 33. The measurements show that the loss in the case of I and II of Fig. 33 is the same, and greater than III of the same figure. The explanation of this is taken to be that the charging current of the different petticoats of the insulator has to be supplied over the surface film of the insulator and that the greater this charging current is, the greater the loss will be. The charging current would naturally be greater in the case of I and II than in the case of III, since, in addition to the condenser effect between the different petticoats of the insulator, there will be a condenser effect between the different petticoats of the insulator and the metal pin inside them. That this matter of the charging current of the insulator has considerable to do with the insulator losses is also shown by Fig. 30, showing losses on insulators of different sizes. When the measurement of Fig. 30 was taken, it was thought that possibly the loss over an insulator was due, simply, to conductivity through a film on the surface of the insulator. If this were the case, it ought to be possible to compare the losses over different insulators by calculating the relative resistances of their surfaces, assuming the surfaces had the same thickness of conducting film. On making such calculations, however, it was found that the resistances calculated in this way would not account for the different losses. Some of the insulators whose calculated film resistances were highest had also the highest loss; but, in every such case, these insulators were of the type in which the petticoats were more nearly parallel to the metal pin, thus offering a better chance for condenser effects between the petticoats and the pin; whereas, the lower losses, obtained in the case of insulators whose calculated film resistance was lower, were obtained from insulators whose petticoats were more nearly horizontal, that is, whose surfaces rapidly departed from parallelism with the pin, offering less chance for condenser effects.

The relation which has been discovered connecting loss and vapor product is not offered herein as a law, but simply as an empiric relation which seems to exist between the quantities involved and which may be put to practical use in determining what will happen under given atmospheric moisture conditions. As previously explained, the vapor product is a product obtained by multiplying together the vapor pressure exerted by the moisture which exists in space under a given set of conditions, by the fraction representing the relative humidity at that time. The relative humidity is the ratio of the amount of moisture in unit space at a given temperature to the amount of moisture which would be contained in the same space if saturated at the same temperature. This ratio is the same as the ratio of the pressures of the vapor. That is if $p$ = the vapor pressure under any given temperature, $t$, and if $P$ = the saturated vapor pressure for the same temperature, we have:

$$\text{relative humidity} = \frac{p}{P}$$

or the vapor product as we have defined it is

$$\text{vapor product} = \frac{p'}{P}$$

The numerator of this expression may be evaluated in terms of the density of the aqueous vapor (*i.e.*, the weight of water vapor in unit space) and the temperature; but the denominator cannot be similarly evaluated. Regnault determined the relation between $P$ and $t$, but the relation has never been rationalized and, apparently, no satisfactory simple empiric formula has been found connecting these two quantities. I have been unable, therefore, to arrive at any rational explanation for the relation which seems to exist between loss and vapor product and, in the absence of such rationalization, this relation must be considered as purely empirical.

It will be noted that the relation between loss and vapor product is even more clearly defined in the case of the insulator losses than it is in the case of the atmospheric losses between conductors. This, as has been previously explained, is probably due to two things. One, that the insulators being near the ground were probably less affected by smoke or other floating particles in the atmosphere; the other, that the humidity measurements were taken alongside the insulators; whereas those applying to the lines were taken on the ground below the lines and at one end of the 1,000 feet of line used. In the case of the humidity measurements, applying to insulators, therefore, these measurements directly apply to the space in the neighborhood of the insulators, whereas in the case of the line, the humidity measurements apply only to one portion of the line and may or may not have fairly represented the average condition over the whole line.

The curves in the case of the insulators, Figs. 28 and 29, have been drawn in as straight lines, although if the measurements on the insulators had been carried to higher values of vapor product, no doubt the curves would have been drawn in slightly curved as is the case with the lower portions of the curves of Figs. 8 and 9.

The vapor product curves for all the cables measured are not given herein, in order to not unduly extend this paper, but they have been made use of in deriving certain other curves. One of the derived curves is that of Fig. 39, which shows the relation between the critical point and the spacing of the conductors at the value of vapor product = 0.20. One of these curves is drawn in broken. The broken portion is an exterpolation.

There is a curious result of this apparent relation between loss and vapor product. If the voltage loss curve for vapor product = 0.0, be subtracted from the corresponding loss curve for any other vapor product, the residual difference seems to be about the same for all sizes of conductors and all spacings. In Fig. 40 are shown these residual quantities obtained by subtracting from the voltage loss curve for a given size cable at different spacings and at vapor product = 0.20, the corresponding loss curves for vapor product = 0.0. As will be seen the residual quantities are not far apart.

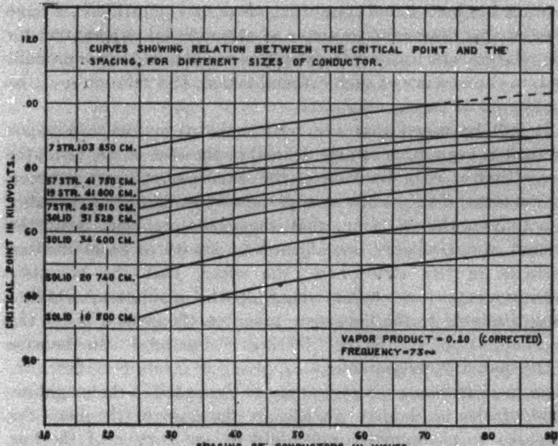


FIG. 39.

In Fig. 41 corresponding results have been obtained for different sizes of conductors at the same spacing. Here again, the residual differences do not differ widely, except at the high voltages where the loss is very sensitive to any change of condition, such as smoke, etc. On comparison also it will be seen that the residual differences are about the same in the two

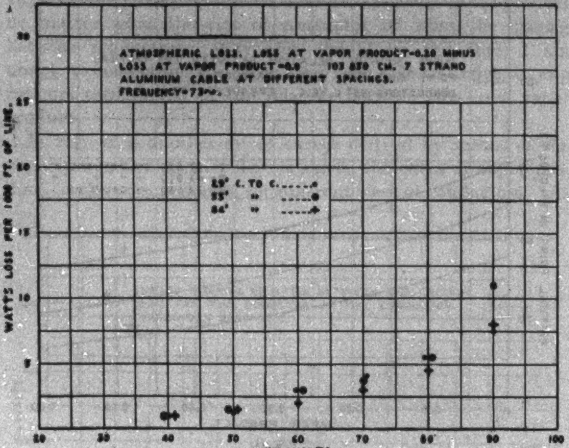

ATMOSPHERIC LOSS. LOSS AT VAPOR PRODUCT=0.20 MINUS LOSS AT VAPOR PRODUCT=0.0 103 850 CM. 7 STRAND ALUMINUM CABLE AT DIFFERENT SPACINGS.
FREQUENCY=73~.
29° C. TO C. ...... •
55° " ...... ●
84° " ...... +
WATTS LOSS PER 1000 FT. OF LINE.
30
25
20
15
10
5
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 40.

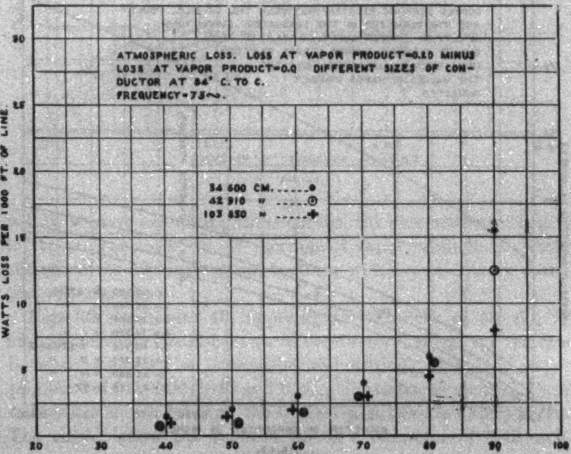

ATMOSPHERIC LOSS. LOSS AT VAPOR PRODUCT=0.20 MINUS LOSS AT VAPOR PRODUCT=0.0 DIFFERENT SIZES OF CONDUCTOR AT 84° C. TO C.
FREQUENCY-73~.
34 600 CM. ...... •
42 910 " ...... ⊙
103 850 " ...... +
WATTS LOSS PER 1000 FT. OF LINE.
30
25
20
15
10
5
20
30
40
50
60
70
80
90
100
KILOVOLTS.

FIG. 41.

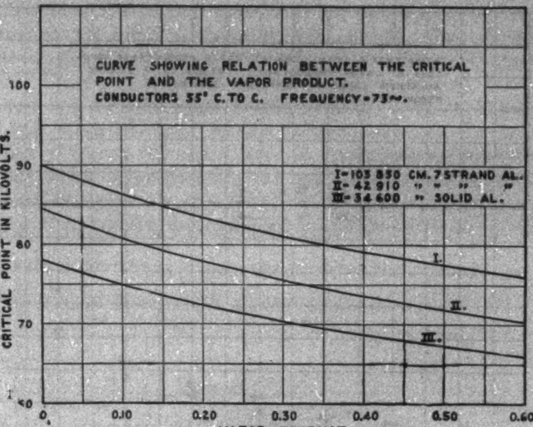

CURVE SHOWING RELATION BETWEEN THE CRITICAL POINT AND THE VAPOR PRODUCT.
CONDUCTORS 55" C. TO C. FREQUENCY-73~.
I-103 850 CM. 7 STRAND AL.
II-42 910 " " " "
III-34 600 " SOLID AL.
I.
II.
III.
CRITICAL POINT IN KILOVOLTS.
100
90
80
70
60
0
0.10
0.20
0.30
0.40
0.50
0.60
VAPOR PRODUCT.

FIG. 42

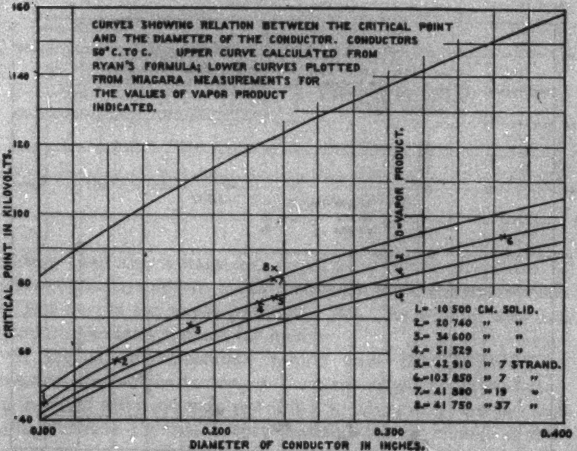

CURVES SHOWING RELATION BETWEEN THE CRITICAL POINT AND THE DIAMETER OF THE CONDUCTOR. CONDUCTORS 50" C. TO C. UPPER CURVE CALCULATED FROM RYAN'S FORMULA; LOWER CURVES PLOTTED FROM NIAGARA MEASUREMENTS FOR THE VALUES OF VAPOR PRODUCT INDICATED.
0-VAPOR PRODUCT.
1.- 10 500 CM. SOLID.
2.- 20 740 " "
3.- 34 600 " "
4.- 51 529 " "
5.- 42 910 " 7 STRAND.
6.-103 850 " 7 "
7.- 41 880 " 19 "
8.- 41 750 " 37 "
1
2
3
4
5
6
7
8
CRITICAL POINT IN KILOVOLTS.
160
140
120
100
80
60
40
0.100
0.200
0.300
0.400
DIAMETER OF CONDUCTOR IN INCHES.

FIG. 43.

figures. Apparently, therefore, the increase of loss due to vapor in the atmosphere is the same for the same vapor product no matter what the size of conductor or what the spacing between conductors. Why this should be the case, I am unable to conjecture, any more than I am able to arrive at any rational explanation of the relation between loss and vapor product.

In Fig. 42 is another set of curves derived by means of the vapor product relation. Here is shown the effect of vapor product on the critical points, for different sizes of conductors. As will be seen on examining these curves, the percentage reduction in the critical point, due to increase of vapor product, is closely the same for all sizes of conductors; which would seem to be properly the case.

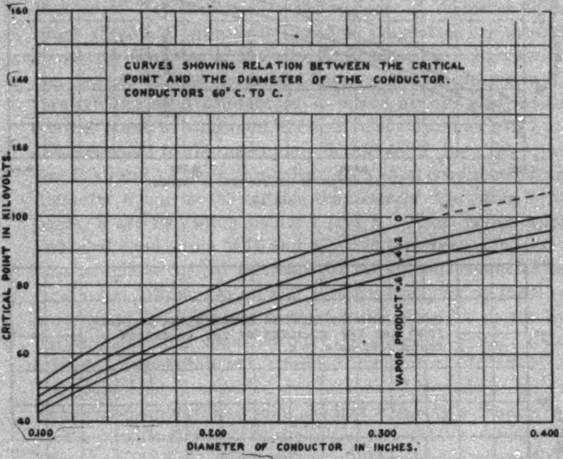


FIG. 44.

Figs. 43, 44, 45 and 46, applying to distances of 50, 60, 72 and 84 inches between centres of conductors, show the relation between diameter of conductor and critical point for vapor products of 0.0, 0.20, 0.40 and 0.60. Portions of some of these curves are shown broken; the broken portions are exterpolated. The curves show the relation up to a diameter of 0.40 inch.

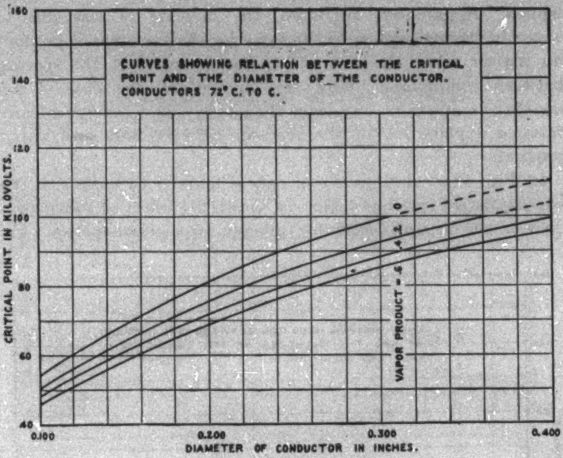

CURVES SHOWING RELATION BETWEEN THE CRITICAL POINT AND THE DIAMETER OF THE CONDUCTOR.
CONDUCTORS 72" C. TO C.
CRITICAL POINT IN KILOVOLTS.
160
140
120
100
80
60
40
0.100
0.200
0.300
0.400
DIAMETER OF CONDUCTOR IN INCHES.
VAPOR PRODUCT = .6 .4 .2 0

FIG. 45.

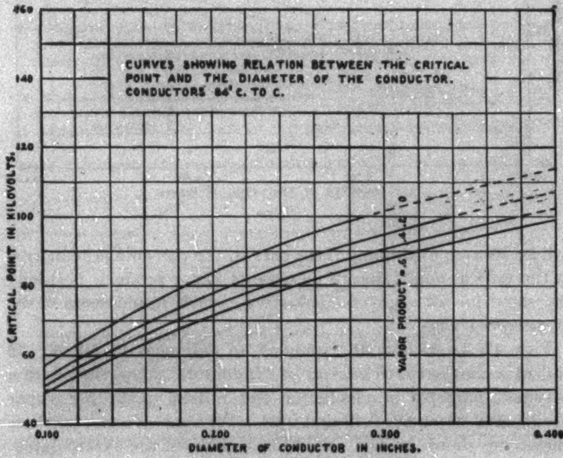

CURVES SHOWING RELATION BETWEEN THE CRITICAL POINT AND THE DIAMETER OF THE CONDUCTOR.
CONDUCTORS 84" C. TO C.
CRITICAL POINT IN KILOVOLTS.
160
140
120
100
80
60
40
0.100
0.200
0.300
0.400
DIAMETER OF CONDUCTOR IN INCHES.
VAPOR PRODUCT = .6 .4 .2 0

FIG. 46.

The maximum diameter of conductor on which measurements were taken was 0.518 inch; but, under all conditions of measurement, the critical point corresponding to this diameter was above the maximum voltage of the transformer, namely, 100,000 volts.

Referring to Fig. 43, particular attention is invited to the curve for vapor product 0.20 which is the only curve whose points are shown. All the points shown in this figure apply to this curve, and are numbered. Beginning at the left hand end of the curve, the first four points are for solid conductors; the next two points (5 and 6) are for stranded conductors of 7 strands each. The values of diameter opposite which these last two points (5 and 6) are plotted are the outside or overall diameter of the stranded conductor. In view of the fact that these last two points fall in well with the curve drawn through the solid conductors, it would appear that, so far as critical point is concerned, the equivalent diameter of a 7 strand cable is equal to the maximum diameter of the cable; that is, the 7 strand cable is equivalent to a solid conductor having a diameter equal to the outside diameter of the cable. Above point, 5 are two other points 7 and 8. These points apply to stranded conductors of 19 and 37 strands respectively, and they, also, are plotted with reference to the outside diameter of the conductor Now, the critical voltages applying to these points correspond to diameters of solid conductors (as shown by the curve 0.20 under consideration) considerably greater than the outside diameter of the stranded conductor. It would seem, therefore, that a stranded conductor of 7 strands is equivalent, as to critical point, to a solid conductor having a diameter equal to the outside diameter of the cable, and that a cable of more than 7 strands is equivalent to a solid conductor whose diameter is *greater* than the outside diameter of the cable.

The upper curve of Fig. 43 is one obtained by means of Ryan's formula (and on the assumption of a sine wave electromotive force) for the same spacing as the lower curves of this figure. As will be seen, the critical points by the formula are much higher than those given by the lower curves even for vapor product = 0.0 (*i.e.*, absolutely dry air). Not only is this the case, but the curve of the formula evidently does not follow the same law as the lower curves. In order to compare the Niagara results with Ryan's formula, the following tables have been prepared, showing the values of critical point from the Niagara measurements, the corresponding values from the formula, and the ratio of the former to the latter.

COMPARISON OF CRITICAL POINTS FROM NIAGARA MEASUREMENTS, AND FROM RYAN'S FORMULA, FOR DIFFERENT SPACINGS OF CONDUCTORS

| Spacings of conductors in inches | Critical points from Ryan's formula | Niagara critical points | Ratio $\frac{\text{Niagara}}{\text{Ryan}}$ |
|---|---|---|---|
| 30 | 112 | 69.5 | 0.62 |
| 40 | 120 | 73 | 0.61 |
| 50 | 122 | 76 | 0.62 |
| 60 | 125.5 | 79.5 | 0.63 |
| 70 | 129 | 82 | 0.63 |
| 80 | 131.5 | 84 | 0.64 |
| 90 | 134 | 86 | 0.64 |

In making calculations by Ryan's formula, the barometric pressure has been taken as 29.5 inches and the temperature 70° fahr.
The Niagara critical points are for vapor product = 0.20.
The diameter of the conductor was 0.2349 in.
All critical points given in effective kilovolts.

COMPARISON OF NIAGARA CRITICAL POINTS, AT DIFFERENT VAPOR PRODUCTS, AND CRITICAL POINTS CALCULATED FROM RYAN'S FORMULA, FOR DIFFERENT SIZE CONDUCTORS SPACED 50 INCHES CENTER TO CENTER

| Area of conductor cir. mils | Diam of cond. inches | Critical points from Ryan's formula | Niagara critical points for the values of vapor product given | | | | Ratio $\frac{\text{Niagara}}{\text{Ryan}}$ for the values of vapor products given | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | .2 | .4 | .6 | 0 | .2 | .4 | .6 |
| 103850 | .3657 | 152 | 101 | 94 | 89 | 85 | 0.664 | 0.618 | 0.585 | 0.559 |
| 42910 | .2349 | 122 | 82 | 76 | 72 | 68.5 | 0.672 | 0.623 | 0.590 | 0.561 |
| 34600 | .186 | 110 | 72 | 68 | 63 | 60 | 0.655 | 0.618 | 0.573 | 0.545 |
| 20740 | .144 | 97 | 61.5 | 57 | 53.5 | 51.5 | 0.634 | 0.588 | 0.552 | 0.531 |
| 10500 | .1025 | 82.5 | 49 | 45 | 42.5 | 40.5 | 0.594 | 0.545 | 0.515 | 0.491 |

In making calculations by Ryan's formula, the barometric pressure has been taken as 29.5 inches and the temperature 70° fahr.
All critical points given in effective kilovolts.

These tables show that the Niagara values vary from 0.49 to 0.66 of those by the formula; the ratio remaining practically constant for the same size conductor at different spacings but varying for the different sizes of conductor at the same spacing. In other words, qualitatively, the Niagara results agree with the formula as the spacing is varied, but depart somewhat from the formula as the diameter is varied; and quantitatively they do not agree with the formula at all.

In order to make Ryan's formula applicable at different diameters and different vapor products Fig. 47 has been prepared, showing the ratio by which the critical points obtained from Ryan's formula must be multiplied in order to obtain for different diameters and vapor products the critical point corresponding to the Niagara results.

As has been previously mentioned (see page 1066) Ryan's formula contains two quantities, $d$ and $D'$, which are not constant. In making use of his formula, the value of $d$ and $D'$ must be taken from a table, given by him, in which they appear as functions of the diameter of the conductor. The formula is not, therefore, self contained.

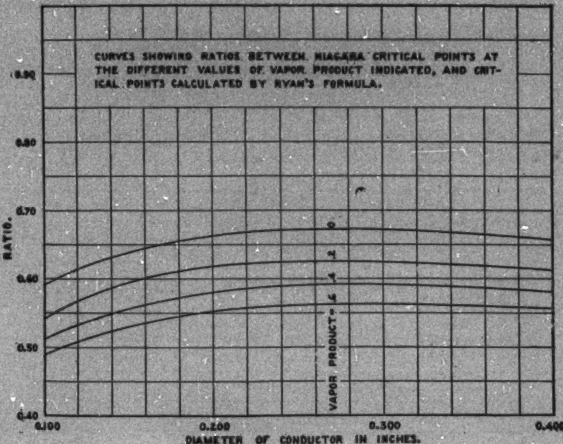

CURVES SHOWING RATIOS BETWEEN NIAGARA CRITICAL POINTS AT THE DIFFERENT VALUES OF VAPOR PRODUCT INDICATED, AND CRITICAL POINTS CALCULATED BY RYAN'S FORMULA.

FIG. 47.

On plotting the value of $d$ and $D'$ as functions of the diameter of conductor, the curves of Fig. 48 are obtained. These curves are hardly such as one would expect in connection with physical phenomena. The relations they show would appear to be entirely empirical and of a character to raise some doubt as to the necessity for the assumptions from which they result.

It is possible to represent quite closely the results of the Niagara measurements by a self-contained expression of the form

$$E = k_1 \left(1 + \frac{k_2}{k_3 + r}\right) (r) \log \left(\frac{s}{r}\right)$$

in which $E$ is the e.m.f.; $r$ the radius of conductors; $s$ the distance between conductors; and $k_1$, $k_2$, $k_3$ constants. The last two variable factors, $(r) \log \left(\frac{s}{r}\right)$, of this expression are similar in form to those of the theoretical equation obtained by the usual method of analysis, so that to this extent, at least, the expression is rational. The other variable factor, $\left(1 + \frac{k_2}{k_3 + r}\right)$, may be looked upon as accounting for the existence and variability of the small quantity $d$, and the variability of the critical dielectric stress $D'$ (if there be any necessity for such).

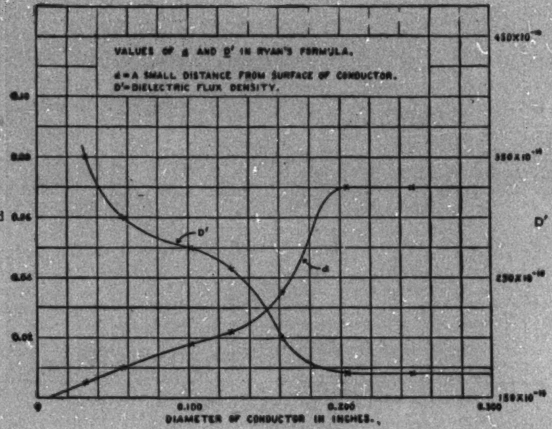


FIG. 46.

Whatever may be the adequacy of the argument in favor of the small quantity $d$, and its variability, it would seem as though $D'$, the critical dielectric stress, should be constant; that any apparent variation in it is more likely due to errors in the method of calculating electrostatic force (such as the assumption of uniform density of charge) than to an actual variation of the local stress necessary to institute breakdown of the dielectric.

The above form of expression applies for any given vapor product. Variation in vapor product may be quite closely taken into account if there be introduced into the expression an additional empirical factor of the form

$$\frac{1}{1+k_4\, p'}$$

where $p'$ is the vapor product and $k_4$ a constant.

The above expressions are not offered as final formulæ; I desire to obtain more corroborative data before proposing a final expression. They do, however, quite closely represent the Niagara results and may be advantageously used in adapting or extending them so far as this may seem to be warranted.

It is not known what frequency Ryan used, but it is presumed to have been 60 cycles. The results at Niagara were at 73 cycles. A difference in frequency might account, in part, for the difference in the results obtained.

In order that the Niagara results shall be applicable to different localities, the following table has been prepared by means of data obtained from the United States Weather Bureau. The table applies to two winter and two summer months.

MAXIMUM AND MINIMUM VAPOR PRODUCTS FOR FOUR DIFFERENT LOCATIONS IN THE UNITED STATES, FOR JANUARY, FEBRUARY, JULY AND AUGUST, 1905, AS OBTAINED FROM THE HUMIDITY MEASUREMENTS OF THE UNITED STATES WEATHER BUREAU

| | | Jan. | Feb. | July | Aug. |
|---|---|---|---|---|---|
| Eastport, Me. | Maximum | 0.347 | 0.124 | 0.465 | 0.440 |
| 76 feet above sea level.<br>Mean Barometer about 30 in. | Minimum | 0.014 | 0.014 | 0.245 | 0.175 |
| Key West, Fla. | Maximum | 0.552 | 0.566 | 0.674 | 0.743 |
| 22 feet above sea level.<br>Mean Barometer about 30 in. | Minimum | 0.0816 | 0.194 | 0.493 | 0.517 |
| St. Paul, Minn. | Maximum | 0.141 | 0.173 | 0.527 | 0.555 |
| 837 ft. above sea level.<br>Mean Barometer about 29 in. | Minimum | 0.0187 | 0.0106 | 0.157 | 0.179 |
| Denver, Colo. | Maximum | 0.199 | 0.072 | 0.413 | 0.418 |
| 5291 ft. above sea level.<br>Mean Barometer about 25 in. | Minimum | 0.025 | 0.0112 | 0.199 | 0.0224 |

## RESUME AND CONCLUSIONS

It is believed that as the result of the work at Telluride, the work of Professor Ryan, and the results at Niagara, the following conclusions are justified. Such of the following items as were originally due to Professor Ryan are so designated.

1. That with a given conductor at a given spacing and under given atmospheric conditions, there is a certain voltage or "critical point" at which a very appreciable loss begins to occur through the atmosphere.

2. That there may or may not be an appreciable loss exist-

ing below this critical point, depending upon the atmospheric conditions.

3. That the presence of floating particles in the atmosphere may produce a loss below the critical point (Ryan).

4. That the presence of moisture in the atmosphere may produce a loss below the critical point.

5. That the presence of moisture in the atmosphere affects the loss both above and below the critical point.

6. That the presence of moisture or floating particles in the atmosphere affects the position of the critical point (*i.e.*, the value of the critical voltage).

7. That the critical point corresponds to a partial breakdown of the dielectric.

8. That the critical point coincides with the voltage at which luminosity or hissing (or both) of the conductors begins.

9. That the critical point depends upon the maximum value of the electromotive force wave and the distance between the conductors.

10. That the critical point depends upon the local rate of fall of potential or dielectric stress at some point in the atmosphere and, therefore, depends not only upon the maximum value of the electromotive force wave and the distance between the conductors, but also upon the diameter of the conductors. (Ryan.)

11. That there is a loss over insulators which is affected by the moisture conditions of the atmosphere.

12. That the variation of the atmospheric loss between conductors, the variation of the loss over insulators, and the variation of the critical point due to the moisture conditions of the atmosphere bear to the vapor product (*i.e.*, the product obtained by multiplying the vapor pressure by the relative humidity) a definite relation which, so far as is at present known, is an empiric one.

13. That the loss over insulators in a fog is very much higher than the loss in dry air, and somewhat higher than that in a heavy rain.

14. That the smoother the surface of the conductor, the less the loss and the higher the critical point.

15. That the stranding of the line conductors reduces the loss and raises the critical point due to the increase of the equivalent diameter of the conductor.

16. That the increase of the equivalent diameter of the conductor is greater the greater the number of strands.

17. That the weathering of conductors (or at any rate the aluminum conductors and probably copper also) does not appreciably increase the loss or lower the critical point.

18. That the loss and critical point are the same for copper and aluminum under the same conditions.

19. That anything which increases the charging current of an insulator increases the loss over the insulator.

20. That the loss over an insulator on a wooden pin is greater than that over an insulator on a metal pin, because the resistance of the wooden pin is in series with the charging current of the insulator.

21. That the atmospheric loss between conductors and the loss over insulators decreases with the frequency. The law of the decrease is not at present accurately known.

22. That neither the critical point nor the loss between cables is affected by variation in the distance of the cables from the ground.

The effect of atmospheric density upon the critical point has been omitted from the above enumeration. This has not been done because of any doubt as to the accuracy of Ryan's results relating thereto, but simply because neither the results at Telluride nor at Niagara were such as to throw any light, corroborative or otherwise, upon this matter.*†

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* Acknowledgment is due to those of my assistants who, under my directions, took the measurements at Niagara. The work was originally intrusted to Mr. Harry L. St. George, assisted in the beginning by Mr. George K. McDougall, and then by Mr. Harry L. Shepherd. Later, Mr. Shepherd was in charge of the work, assisted at first by Mr. McDougall and then by Mr. Walter I. Tamlyn.

† Acknowledgment is also due the following for assistance rendered.

To the Niagara Falls Hydraulic Power and Manufacturing Company for the use of the land on which the work was carried out; for power supplied without charge; for construction work done at cost; and for many other conveniences without which the work would have been greatly hampered. To the Aluminum Company of America for the loan of wire and cable. To the Weston Electrical Instrument Company for the donation of special instruments. To the Westinghouse Electric and Manufacturing Company for the loan of a motor and instruments. To the Niagara Falls Power Company for the use of their laboratory in the calibration of instruments. To Mr. W. S. Moody of the General Electric Company for the pains which he took in designing the transformers to meet the rather severe requirements of this work.

## DISCUSSION ON "HIGH-VOLTAGE MEASUREMENTS AT NIAGARA."
## ATLANTIC CITY, N. J., JUNE 30, 1908

**Henry L. Doherty:** This paper is a most valuable contribution to a subject of great importance. I will not attempt to discuss any of the details of the paper for fear it will distract from the broader matters which are worthy of consideration.

As a preface to my remarks I want to say, first, that the American Institute of Electrical Engineers is now a body of great importance, and it is in a position to exercise a pronounced influence upon the educational, industrial and commercial progress of this country; and second, that few, if any, other organizations can boast of greater aggregate intelligence or influence than can this organization. Its members are in touch with nearly every class of people, and their individual work and opinions are universally respected.

This paper deals with the researches made to secure a greater knowledge of the problems which underlie the methods for transmitting electrical energy.

Had my time permitted, I would have offered to the Institute a paper at a much earlier date, covering the various methods for the transportation of energy in its various forms, and would have attempted to show the relative cost of transporting energy, or its material, by various means, such as: (a) electrical energy by transmission at high voltage; (b) natural gas by means of pipe-lines; (c) coal and oil by rail; (d) oil by means of pipe-lines; (e) steam and hot water by means of pipe-lines.

I think it can readily be demonstrated that, where a good load factor exists, transportation of energy can be secured at the lowest possible cost by means of electric transmission.

We often find ourselves, as engineers, greatly handicapped by the sentiment prevailing amongst bankers and investors to whom we must look for the necessary funds to finance our undertakings. Often the method of presentation will do much to influence, favorably, prejudiced investors capable of furnishing funds for the enterprise.

It was my intention to show that these so-called "long-distance transmissions" constituted a problem in transportation which could be reduced to the same terms as railroad statistics—which are always available—and their commercial efficiency measured by a comparison therewith. It was my belief that such a comparison would put this whole field of work on a more substantial basis in the minds of the public and increase the activity in this line of work, thus greatly increasing our usefulness.

As my own time will not permit, and as there are many men in the Institute who can do this work much better, I am taking the liberty of suggesting this comparison in relation to the consideration of this subject.

I believe the engineer, and the engineering organization, have been undergoing an evolution which will materially change their scope of usefulness. The engineer must now know, with more or less intimacy, other lines of business; and, as an example, he must know more or less of financial methods and possibilities. He must often interject his engineering methods into other lines of work—in fact, it is remarkable how many of our general business matters are capable of solution by engineering methods and engineering laws. He must know how to state his conclusions in such form as to give readily a clear and correct impression to men educated in other lines of work. The engineering society must not only know the needs of its own members, but must know how to influence other classes of people for the benefit of its own class.

The recent conference called by President Roosevelt for the conservation of our natural resources was, to my mind, a great stroke of statesmanship; and, using this occurrence as an illustration of my preceding statement, it seems to me that as the members of the Institute represent an immense sum of knowledge on this problem—which we all recognize is a matter of national importance—it would not be impertinent for the organization to undertake to contribute materially to the solution of this problem and to make all parties in interest know that it is in a position to do so, and that it should be considered as an important factor in this work. It is hard for me to refrain in any discussion from applauding the excellent work done by this Institute in recent years; and I avail myself of every opportunity to urge that it do still more, and still further widen its field.

Regardless of the other contributions made by Mr. Mershon, I want to point out particularly that he has demonstrated that it is possible to secure financial support for practical research work of this character. This demonstration may prove of greater value to the future achievements of the Institute than any specific work heretofore presented to it. I strongly urge that the Institute should place on record, in unmistakable terms, its appreciation of the generosity of these men, and that at this meeting an effort be made to point out to everybody that such contributions cannot help but prove, if properly directed, great factors in our industrial progress and great factors in the commercial prosperity of this country as a whole.

While many may believe that an organization of this sort should attempt to exert influence only over its own members, here is an excellent example of how it may exert influence over men of great wealth, who are willing to contribute liberally to our research work if it promises benefits to the industrial progress of the country. It seems to me not hard to point out the great value of such contributions.

**Elihu Thomson:** Mr. Mershon some time ago told me of some of his results, and asked me if I could make any suggestions as to the cause; that is, as to the actual thing happening; if I could suggest some physical conception. Before I make any attempt at this—and it can only be an attempt—I should say that there is true gratification felt in finding that funds can be at times available, and may in the future be more frequently available, for engineering research as distinguished from pure scientific research. Yet the results of the paper while quite practical, as applied to transmission lines, have, further, germs of scientific progress in them—progress along the lines of pure science.

I will not take the time to discuss in detail the various matters of the paper. Perhaps it would be well to turn to the last pages and take up the final conclusions, and note, if we can, whether the results appear to be rational or not. The "critical point" is well understood; and I do not see, in reading over Conclusion 1, that there is anything to be said further; there is a certain voltage called the "critical point" at which a very appreciable loss begins, and that point is coincident with the visual manifestations, corona, or decomposition, or static breakdown, of the dielectric surrounding the conductor.

Conclusion 2 reads, "That there may or may not be an appreciable loss existing below this critical point, depending upon the atmospheric conditions." It seems to be a remarkable result, where no visible effect can be found around the conductor, that there is still even with air in a dry condition, a notable loss.

Conclusion 3 reads, "That the presence of floating particles in the atmosphere may produce a loss below the critical point (Ryan)." That, I think, we can readily understand; the particles may be attracted to the conductor, and may be the means of causing a diffusion of energy—they may be pulled, as it were, towards the conductor, breaking down the homogeneity of the dielectric and thus causing a loss of energy.

Then, again, we read in Conclusion 4, "That the presence of moisture in the atmosphere may produce a loss below the critical point." Here we find that Mr. Mershon has given us conditions under which the moisture produces a loss depending apparently on the amount of water present in a given volume, that is, on the absolute vapor pressure of the water and the condition of the water as to its being more or less near condensation, or whether it is further from the condition of condensation or nearer to it. This leads us, I think, to the consideration of the fact that water vapor just above its vaporization point cannot be considered as a true gas. It has to be heated considerably beyond its vaporization point to become a true gas. In a gas, according to the kinetic theory, the molecules are flying about and colliding in all directions; they have a certain velocity, but the velocity is not uniform, some molecules being accelerated beyond the mean velocity and others very definitely retarded below the mean velocity. Now, when a liquid is near condensation, some of these molecules may be robbed almost entirely of velocity, but we know that if this occurs in a vapor, such as water vapor, such molecules may be considered as for a very brief time in the liquid state. Afterwards they are again separated by colliding with other molecules at higher velocities. In other words, in this instance there is an unstable condition in the gaseous substance, and the nearer therefore to condensation, or the greater the humidity—relative humidity—the more this factor will come in; the state of some small fraction of the water vapor being changed from that of a gas to a liquid. A larger number of molecules are then in a state of quiescence, for the time being, or in the state of water for a very short interval, the nearer the approach to condensation. This condition would explain why the vapor product—if our theory is correct—is concerned. According to the result obtained by Mr. Mershon the vapor product must be taken; not only the amount of vapor water present, but the state of that water. The number of molecules of water vapor so condensed, as water—or so losing their velocity and becoming for the time being, only instantaneously, more or less liquid—would be greater with the greater amount of water, as expressed by the greater vapor tension of the water, and greater also the nearer to the point of condensation, or the greater the humidity. We must infer from this, however, that the molecules of water in the quiescent condition have some unusual power of absorbing energy; that they can receive energy, can be accelerated or can be decomposed or driven apart by absorbing energy from the conductor. This action might go on invisibly, it might simply be that the water is, as it were, electrically evaporated or put back into its high-velocity condition by energy expended. This view is merely put forward as a suggestion, depending on the validity of our ideas of the action of molecules of gas; bringing together Conclusions 3 and 4, "That the presence of floating particles in the atmosphere may produce a loss below the critical point" and "that the presence of moisture in the atmosphere may produce a loss below the critical point."

Conclusion 5 is as follows: "That the presence of moisture in the atmosphere affects the loss both above and below the critical point." I think this would naturally follow from the other idea, that the more water the more loss would occur, even above the critical point; that the particles would be in condition to carry away more energy, on the assumption that water particles have an exceptional capacity in that direction.

Conclusion 6 is as follows: "That the presence of moisture or floating particles in the atmosphere affects the position of the critical point." This, again, means that the water particles, or the moisture particles, would act as a sort of intermediary in extending the influence around the conductor, and accentuating the production of the critical point; or in other words, the water would be more readily ionized than dry air, and become the medium for the absorption of larger amounts of energy, causing dielectric breakdown.

Conclusion 7 reads: "That the critical point corresponds to a partial breakdown of the dielectric." That, of course, we can readily assume.

Conclusion 8: "That the critical point coincides with the voltage at which luminosity or hissing (or both) of the conductors begins." Either the sound or the luminosity may be an index of the breakdown—actual sparking into the dielectric, and a reversal of current flowing through a short distance with each alternation, and naturally this would be equivalent to a high-resistance leak around the conductor, causing loss.

Conclusions 9, 10, and 11 are as follows:

9. "That the critical point depends upon the maximum value of the electromotive-force wave and the distance between the conductors.

10. "That the critical point depends upon the local rate of fall of potential or dielectric stress at some point in the atmosphere and, therefore, depends not only upon the maximum value of the electromotive-force wave and the distance between the conductors, but also upon the diameter of the conductors (Ryan).

11. "That there is a loss over insulators which is affected by the moisture conditions of the atmosphere."

I do not think there is much necessity for my commenting upon these conclusions. They seem to be the natural results to be expected and are fairly well known.

Conclusion 12 reads: "That the variation of the atmospheric loss between conductors, the variation of the loss over insulators, and the variation of the critical point due to the moisture conditions of the atmosphere, bear to the vapor product (*i.e.*, the product obtained by multiplying the vapor pressure by the relative humidity) a definite relation, which, so far as it is at present known, is an empirical one." In that conclusion we come to the particularly novel point, namely, that we must have not merely the amount of moisture, not merely the saturation, but we must multiply together the amount of moisture present, or the amount of water vapor, by its state or condition, so to speak, which I have above suggested as that of more or less imperfect gas.

Conclusion 13 reads: "That the loss over insulators in a fog is very much higher than the loss in dry air, and somewhat higher than that in a heavy rain." This can be easily understood. If the whole insulator were covered with water, the conduction over the upper surface of the insulator would undoubtedly be greater than if it were covered with fine particles of water. Its upper surface would be, in other words, of lower resistance and therefore cause less loss than if the fog settled upon the surface and made it a very high-resistance surface.

Conclusion 14 reads: "That the smoother the surface of the conductor, the less the loss and the higher the critical point." We would be naturally ready to admit this, on account of the absence of projections or points; but 15, which reads: "That the stranding of the line conductors reduces the loss and raises the critical point due to the increase of the equivalent diameter of the conductor," seems to be inconsistent therewith. With the stranding of the line conductor we would reach a limit, of course, very soon. The continued finer and finer stranding would not give a continued increase in real diameter, as the spaces between the wires of large or small gauge are relatively the same, so that we seem to be, in Conclusion 15, roughening the conductor and reducing the loss thereby. Conclusion 16 reads: "That the increase of the equivalent diameter of the conductor is greater the greater the number of strands." Here we have roughened still more by making the strands fine and thus have a large number of spiral projections or ridges all over it, and yet the increase of equivalent diameter is greater; whereas under Conclusion 14 it is said that the smoother the surface of the conductor, the less the loss and the higher the critical point. These things seem to need further investigation and some explanation, because they do not seem to be consistent. One can imagine that the stranding could go on until the conductor was covered with extremely fine ridges, and then we should consider it as possessing a rough surface; not an irregular roughness, but ridges nevertheless.

Conclusion 17 reads: "That the weathering of conductors (or at any rate the aluminum conductors and probably copper ones also) does not appreciably increase the loss or lower the critical point." I do not know that we should expect to find any great difference between conductors of aluminum or copper, as referred to in this Conclusion, or that a slight film of oxide would have any particular effect on the losses.

Conclusions 18 and 19 are as follows:

18. "That the loss and critical point are the same for copper and aluminum under the same conditions."

19. "That anything which increases the charging current of the insulator increases the loss over the insulator."

I think this we could admit. If the insulator dielectric were free from all dielectric hysteresis, then, of course, we would not expect Conclusion 19 to hold, but with ordinary materials it would undoubtedly be true that the loss would increase with the increase of the charging current. It would hence follow that if we interpose layers of air between the insulator pin and the wire or conductor, and these layers of air have the total effect of reducing the charging current very considerably, we may save some loss from the insulator. On the other hand, if we introduce only thin or moderately thick layers of air which have to be worked across by blue discharges, or anything of that sort, then of course we increase the loss by dividing the insulation. This comes directly in line with Conclusion 20, which reads, " That the loss over an insulator on a wooden pin is greater than that over an insulator on a metal pin, because the resistance of the wooden pin is in series with the charging current of the insulator," and would point to the fact that if we use a metal pin and want to avoid the losses as much as possible, we should make the metal pin fit the insulator very closely by some sort of conducting filling, and not have any space to be worked over by discharges from the pin to the inside surface of the insulator; but that is probably not of very great consequence.

Conclusion 21 reads: " That the atmospheric loss between conductors and the loss over insulators decreases with the frequency. The law of the decrease is not at present accurately known." I think this might naturally be expected, as the greater frequency would stress the dielectric more times per second, although a single long wave would no doubt give more loss than the shorter wave of equal amplitude.

Conclusion 22 reads: " That neither the critical point nor the loss between cables is affected by variation in the distance of the cables from the ground." I suppose this follows, because in ordinary cases the cables are at such distances from the ground that there is none of the effect of incipient brush discharge and increase of loss, such as we have when the conductors themselves are near together.

I have to say in regard to the paper, that it is certainly a very interesting and valuable one, and points the way to further useful investigation.

**Samuel Sheldon:** Professor Barus, at Brown University, and members of his department, have carried on very extensive investigations as to the conditions of the atmosphere in the vicinity of Brown University, in Providence, and also on Block Island, which is pretty well out to sea, with the result that he finds ions always present in the atmosphere at both places. Now these ions each have upon them a definite charge of electricity although they are of various shapes and conditions. If one of these ions be placed in an electrostatic field of a given intensity, a force is exerted upon it which is equal to the product of the charge times the strength of the field. Townsend has determined that under a given set of conditions a very definite and measured amount of energy is necessary to produce by impact ionization of un-ionized or non-ionized particles.

Under given atmospheric conditions there is an average free path between the particles that may come into collision; and if the collision represents a sufficient amount of energy, ionization of the particle that is struck will take place. The fact that energy is equal to half the mass times the square of the velocity, and that the velocity squared is twice the acceleration times the distance through which the particle moves, taken in conjunction with the fact that with the same force the acceleration is inversely as the mass, shows that irrespective of the size of the particles, if the latter move over the same distances, under the same force, they will arrive at the end of these distances with the same energy. If, therefore, they come into impact and the field has been sufficiently strong, ionization will take place. There will result more ions than were present before, and these again will set up further ionization, and therefore, ionization will spread like a disease in a field of sufficient intensity, until there are a sufficient number of ions to carry a discharge by convection. This explains many of the results which Mr. Mershon has obtained.

**Henry Floy:** While the Institute is certainly to be felicitated on being the medium through which the valuable data collected by Mr. Mershon is to be transmitted to the engineering world, and while Mr. Mershon is to be congratulated most heartily at the happy outcome of this long and tedious experimentation, there is another fact brought out by this paper which is particularly interesting to me, one which Mr. Mershon and Mr. Doherty have already touched on, and that is the disinterested generosity of Mr. J. E. Aldred, Mr. Frederic Nicholls, Mr. James Ross, and Mr. George Westinghouse. It seems to me that the engineer has now reached a point, at which I have long hoped he would arrive, where in the minds of commercial business men he is no longer considered only a theorist and scientist. And so we now have a most encouraging example of practical business men entrusting, in an unrestricted manner, their funds to a scientist for carrying on an investigation in his own way. The precedent thereby established seems to me to mark an era in the engineering world. If we can only encourage men of financial ability to subscribe funds to those engineers who are as capable as Mr. Mershon is to originate and carry out a series of tests and experiments, we have gone a long way in advance of previous achievement.

The results and conclusions reached by Mr. Mershon are very complete, surprisingly so to anyone who has attempted to carry on a set of experiments of this sort, particularly when it is realized that any one of an innumerable number of accidents might have vitiated the entire results.

With regard to the deductions made by Mr. Mershon, perhaps the most disquieting in the whole paper is the one shown, for example, by the curves in Fig. 43, showing the relation between the critical point as determined by his experiments and those of Professor Ryan. Mr. Mershon has noted that his critical voltages are about sixty per cent. of Professor Ryan's results. This difference seems to me most extraordinary, and as far as I know Mr. Mershon has not offered any explanation of it. I had hoped we would hear from Professor Ryan with regard to this matter. It is possible that part of the difference may be accounted for by the failure of Professor Ryan to have accurately determined the points of luminosity. As I understand his experiments, his critical points were determined mainly by visual observation, and if he did not fix the points exactly owing to personal equation or to failure to carry on his experiments in a room absolutely devoid of light, his voltages would be higher than Mr. Mershon's, who determines his values by a continuation of the lower curve. This difference in method, however, would not, apparently, wholly account for the great difference in the voltages at the critical points. While I am unable to criticize Mr. Mershon's method, it would seem as if his voltages were somewhat low. Turning to Fig. 43 and assuming the vapor product of 0.4, and the diameter of the conductor as one-quarter inch, we find that the critical point in kilovolts is 75. From what I have heard of the line at Grand Rapids, Michigan, where they are operating at 75,000 volts, and at other very high-tension installations, luminosity does not appear on those lines. It may be that the conductors are more widely separated or of different diameter, or that the vapor product is not as given in this table; but it would seem as if in the course of their operation there would be some fluctuation in the voltage or variation in conditions so that luminosity would be observable. Under the conditions stated by Mr. Mershon, luminosity should appear at 75,000 volts.

It would seem as if further investigation, perhaps by some other or outside party, should be carried on to determine whether Mr. Mershon's results can be absolutely relied upon, or whether the figures previously given by Professor Ryan are nearer correct. It would be unnecessary to repeat the experiment throughout, but simply to check a few points on certain curves. The location of the critical point is certainly a very vital question with engineers who are designing high-tension lines.

The announcement by Mr. Mershon of the less resistance of wooden pins, as compared with iron pins, is certainly astonishing to most of us, but in view of his measurements and the explanation given, we must acknowledge it as a fact.

In regard to the insulators, Mr. Mershon apparently tested no suspension-type insulators. Of course, tests of these insulators would have been especially interesting at this time, as they are coming more and more into use. Although he does not say so, his statement indicates he has learned the ideal form of insulator for a given voltage. Perhaps, in another paper, he will give us an idea as to the form of the insulator, and the number of petticoats which this ideal form of insulator should have, for a given voltage.

**Chas. P. Steinmetz:** Mr. Mershon has given us a very valuable paper, increasing our knowledge of what takes place in conductors when they reach such high voltages that the air surrounding them ceases to be insulating, begins to break down.

He has proved again the law given some years ago, and illustrated in his paper, that the voltage loss is a curve of two branches—one at lower voltage, of very small loss, and the second branch at high voltage, rising very rapidly. There is one point, however, concerning which I cannot agree with him, and that is the method of determining the critical point as the point where deviation begins from the lower branch, as seen in Fig. 38. I do not think that is the correct critical point. We must expect that the conductor and surrounding conditions are not absolutely uniform, and that the transition from one condition to another one can only be gradual. The first beginning of a brush discharge at some isolated point, some kink in the conductor, cannot be considered as the voltage where the breakdown strength of the system has been reached all over the conductor, and I believe this feature may account for the discrepancy between Professor Ryan's and Mr Mershon's results. I also agree that it would not be proper to take as the critical point the point where the upper or higher curve is perfect. Theoretically if we had the equations of the lower curve in Fig. 38, and of the upper curve, the point of intersection would be the proper critical point. This would be at higher voltage than that assumed by Mr. Mershon. We obviously cannot do this, as we do not have the equations of the two curves; and by estimating it, by continuing such curves, it is very difficult to get anywhere near accurate results; that is, results from which you can derive numerical values of the breakdown strength of air.

I should therefore suggest a slight modification of the method, which may give accurate results or may not. It is to plot the curve in Fig. 38 with the logarithm of the ordinate against the logarithm of the abscissa. Both branches of the curve may theoretically be expected to go through the origin, and such curves going through the origin, can frequently, at least within a limited range, be expressed by some power of the abscissas, that is, by a curve of the equation: $y = A x^n$. If you now plot logarithm $y$ against logarithm $x$, you get a straight line. If in Fig. 38 you were to plot the logarithm of the ordinate against the logarithm of the abscissa, you may get two straight lines, one extending up to 70,000 volts, and the other extending from 80,000 volts upwards, connected with each other by a curved branch; and where you have straight lines, at least for some distance, it is very easy to extend them and so get the point of intersection very sharply, which gives the critical value with much greater accuracy than it can be derived by extrapolation from the original curve. It all depends on the character of the two curves, whether they will give straight lines in the logarithmic representation or not, but it is quite likely they may do so, or at least the deviation from the straight line will be small, and therefore this method should be tried.

While the results, as derived here, are extremely valuable in showing the existence of the critical value, we really want to have more than that. We would like to get the exact numerical value of that critical voltage, and compare it with the conductor diameter, and from that calculate the potential gradient at the conductor surface, and compare it under different conditions; and also compare it with that derived from the striking distances with needle points, where you get the analogous effect. After determining numerically the breakdown strength of air, or its breakdown gradient, very many of these features could be predetermined theoretically and pre-calculated. For this work, very interesting and valuable data are afforded by this paper. We all agree that the future of power transmission depends on going to higher and higher voltage, and you see that the loss of power from the line increases enormously with the increase of voltage beyond the critical point, and so would limit the permissible transmission voltage. Now, if we know how this loss depends on conditions of conductor surface, conductor diameter, etc., it would be a question of engineering design how to lay out the conductors of the transmission line, so as to be able to use as high voltage as possible, and still have a negligible static loss into space.

**Percy H. Thomas:** There are two broad aspects from which this paper may be viewed: first, that of commercial transmission work; secondly, that of the scientist. In the first aspect, what we need to know is whether this loss from conductor to air is going to actually limit the development of power transmission. I think we can say, pretty conclusively, from Mr. Mershon's results, that for the immediate future, at any rate, these losses are commercially practically negligible. The experiments have been so carefully made and their results so carefully stated, that unless some very extreme conditions arise, they will not have to be done over.

In regard to the scientific aspect of the paper, there are a number of comments which I would like to make.

I was very much interested in Dr. Thomson's explanation as to the cause or the physical meaning of the relation between loss and vapor product. Personally, I had not been able to find any consistent hypothesis. His explanation seems to be very reasonable. I ask him if his conception as to the manner in which the molecules or minute particles of water act is as convectors of electricity?

**Elihu Thomson:** They absorb energy by being separated, again by re-evaporation. The mere addition of energy to a perfect gas would, of course, require more energy to accelerate the molecules, to take up their liquid state; and we know it requires considerable energy to convert this condensed or partially condensed product into a gas.

**Percy H. Thomas:** As in the case of the pith-ball and charged disc?

**Elihu Thomson:** It may act as a convector or absorber, and may be ionized more readily also.

**Percy H. Thomas:** That seems reasonable.

This loss is one of the most difficult scientific measurements the engineer has to make—the measurement of true losses at very low power factor and high tension. The method thus becomes of extreme importance. Mr. Mershon has taken very great pains to get a good method, and to check it in all ways possible. In the absence of further data I do not see any reason to expect any error in it, but I do not feel fully convinced, by his check measurements alone, that he has eliminated all possible sources of error. I do not mean to say I suspect any error, but I do not quite consider these checks themselves wholly conclusive.

I wish to suggest another method of making these measurements quickly, which I have tried, and which I consider much simpler in many ways. This is an old method for high-tension measurements—the use of the quadrant electrometer as a wattmeter. Such an instrument was discussed by Miles Walker in a paper read before the Institute at the annual convention in 1902, under the title of "The Electrostatic Wattmeter in Commercial Measurements." The description of certain measurements made with this wattmeter will be found in a paper presented by me at the annual convention of the Institute in 1905, entitled "The Experimental Study of the Rise of Potential of Commercial Transmission Lines, Due to Static Disturbances Caused by Switching, Grounding, etc."

One other suggestion. Often the best method to eliminate a good many of the difficulties is to use a large-capacity apparatus. It is a great handicap to start off with a small transformer in large work, as it is necessary to correct for the errors introduced by the transformer itself. If it had been possible to use a 1,000-kw. generator, and a 1,000-kw. transformer, a great many of the possible causes of error would not have had to be considered.

There are some minor points I would like to bring forward. I would like to ask Mr. Mershon if he has any numerical data on the actual loss during a rain storm?

Some of the vapor-product series are straight lines—those which show the loss on insulators—and others are given as curves. The points are such that it is difficult to tell whether they should be drawn as curved or straight lines. Is it possible they should all be drawn as straight lines?

The losses on the insulator with the pin and without the pin are given. I think Dr. Thomson brought out the point there, that the discrepancy may be due not only to the greater distance the charging current has to come without any pin, but to the presence of loss in the dielectric itself. The dielectric loss may be the cause of the decreased loss with the pin removed. When the pin is in, there is a greater concentration of potential on the head of the insulator than in the other case, and that, as is well known, may cause very serious losses in the dielectric when the concentration is somewhere near the puncture point.

There is another difference between Mr. Ryan's method and

Mr. Mershon's, if I remember, Mr. Ryan projected the vertical part of the loss curve down, to get the critical point, while Mr. Mershon estimates the point of tangency. I may be mistaken, but if I am not, there should be quite a difference in the critical point obtained from the same curve by the two methods, and each method should be judged by its own results. When this is considered, the discrepancy appearing between Ryan's and Mershon's curves would be very materially reduced.

I would like also to ask how the points fall on the loss curve above the knee of the curve. The points given do not run up around the knee. It would be interesting to know how well they fall on the curve above the knee.

**Ralph D. Mershon:** Fig. 22 gives that.

**Percy H. Thomas:** That is just around the knee?

**Ralph D. Mershon:** They come very much closer.

**Percy H. Thomas:** That seems to me remarkable. It would be interesting to have the insulator, *A*, identified, or a more complete drawing of it given. That is the insulator which shows the least loss.

I would like to ask also whether there is any possibility that the losses in the cords from which the wire was held would affect these curves at all? Of course, that loss is pretty small, but if the cords stayed out in the atmosphere even one day, there might be some change.

**Ralph D. Mershon:** A check was taken on the cords each time.

**Percy H. Thomas:** It is interesting to link this phenomenon with the usual brush discharge. With needle points, separated somewhere near the sparking distance of the applied voltage, there is a strong brush discharge, and there is an enormous loss. If the distance is not too small—say three feet—the sparking distance will be almost the same with point terminals as with spheres or other large-diameter terminals. This result is different from the results which are given in Mershon's curve, which we still believe to be right, wherein the smaller-diameter conductors show a much larger loss than the larger conductors. These two results must certainly be consistent, and probably indicate a loop curve in the form shown in the figure. If we have transmission lines separated say 29 in., as the closest distance we have in the paper, the loss with different size conductors varies considerably, but with any given conductor will increase as the distance is decreased, until puncture finally occurs. I imagine we can draw the loss curve for a small conductor as the voltage increases, as shown somewhat by the full line. For a larger conductor the loss does not start at so low a voltage, but it does rise in the end as shown in the dotted line, and judging from the fact just stated that needle points and spheres have equal puncture distances, these two curves approach each other. The explanation probably is that as the smaller conductor begins to discharge actively the strain is transferred from the conductor itself to the region of air around it, and is then restrained there. At a little higher voltage, or closer distance, the larger-diameter conductor begins to discharge current, and is then on an equality with the smaller. After this critical starting point is once reached, it is the convective resistance of the air which determines the leakage to the air. If this hypothesis turns out to be true, it will probably be found that the loss curves for the smaller and the larger conductors approach each other as the puncture points come nearer and nearer. Of course, that is beyond any practical limit for commercial work.

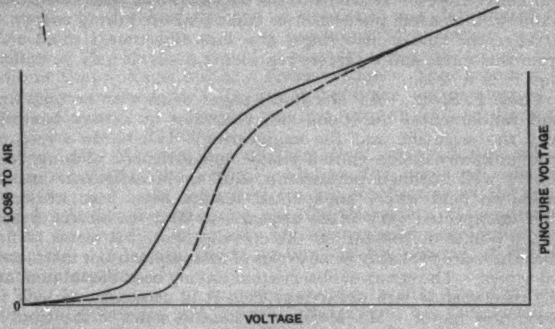

Fig. 1

**P. M. Lincoln:** A question has occurred to me the answer to which I do not find in the paper—and that is, the question as to the influence of the potential of the ground with respect to the potential between wires. Mr. Mershon's curves are all plotted with reference to the potential between the wires. If he was working with a single phase, as I assume he was, then the ground potential may safely be assumed as half the potential between wires. However, in a three-phase system the potential to ground does not remain one-half of the potential between wires, but approximately 58 per cent. of it. The question occurs to me, whether or not this difference of potential has any effect on the loss which will take place in these wires. Again, in case a three-phase system becomes grounded, what effect does that have on the loss? Will the loss be decreased or increased? The potential between the wires will remain the same, but the potential of the conductors to ground will be very different. That is quite an important question, and has an important practical bearing.

**Carl Hering:** While at Niagara Falls some ten or a dozen years ago I noticed a phenomenon which may have some bearing on a point raised in the paper, and touched on by Professor Thomson and Dr. Sheldon, namely, a possible loss of energy into the space surrounding the high-tension transmission wires. I was riding on a steam train which was close to the high-tension transmission lines, and the smoke or steam from the locomotive passed across these lines. As it crossed the wires, I noticed that it formed itself into circular rings around the wires as centers. Presumably they were hollow cylinders, but I could see only the ends, which were circles. It was quite a striking phenomenon. I called it to the attention of a number of those near me, and they all perceived it. It was at the time of one of our conventions. It seems to me this shows at least two things, namely, that some phenomenon takes place requiring energy, to arrange the smoke into rings, and that this energy must come from the wires, and therefore represents a loss; it may be trifling, but it is a loss.

**Chas. F. Scott:** Mr. Mershon's paper deals with certain large and fundamental questions and combines in a very beautiful way the scientific and the engineering. It records a research into unknown fields—not a simple measurement of some facts pretty well outlined beforehand, but an investigation into an unknown field where unexpected results have been obtained. The unexpected very often appears, at first, to be the erratic. If the points do not fall on the curve properly, it seems at first that there are probably some errors of measurement, or instrumental errors. The errors of observation having been eliminated, and the discrepancy still occurring, then it is necessary to look for some new factor. Mr. Mershon intimates some of the troubles he had in discovering these new and erratic elements, and it seems to me that one of the most beautiful things in the paper is the manner in which he set about to discover what was the matter with the vapor. He was pretty sure beforehand that the vapor had not anything to do with the case. His former tests and Professor Ryan's tests had apparently established the fact that the vapor was not a variable factor, but when he finds troubles, he begins to investigate as to the vapor. He does not know what the law is, but he sets his assistants to work to make all sorts of new combinations of vapor constants, and they finally fall upon one which seems to account for and explain the phenomena observed. The law may admit of scientific explanation, and in short be quite obvious now that it has been discovered. The point I want to make is that Mr. Mershon worked in the dark, and worked with no guide, and he finally came across this " obvious " conclusion.

Another thing is brought out in the same connection—a matter which can be worked out in the laboratory, and measured under laboratory facilities and laboratory conditions, may unfortunately, and sometimes in a very discouraging way, prove ineffectual and incomplete when it gets out on a practical transmission line. Lightning arresters may be cited, and observations and measurements like those of Professor Ryan—not because the laboratory may not have gone as far as it could, but because it cannot anticipate all the outside conditions.

This paper, and the things it deals with, are fundamental, because they set certain limits to electric power transmission. Mr. Mershon in another paper, which he worked out with great elaboration some two years ago, sets forth the economic voltage to be applied for transmission to different distances, and the size of conductor which would be used in transmitting power to different distances with the greatest economy. It happens that the diameters of conductors to be used with certain voltages, at certain distances, all fell within the limits of loss. For example, a wire half an inch in diameter was determined by Professor Ryan to have a loss beginning at a certain critical voltage. Mr. Mershon found it was not desirable to use that wire at that voltage, but at a lower voltage. That seems to be a happy circumstance. It would be quite unfortunate if it were necessary, for example, to use a wire an inch in diameter to avoid loss at 25,000 volts.

Now, Mr. Mershon has unfortunately changed one set of these constants, the critical voltages for wires of different diameter, and I am not sure from my recollection of the other paper whether he can now use the diameters of conductors which he found in his paper on transmission economics were desirable. If he can touch on that in his résumé, it will be quite interesting.

This brings into prominence another point, the difference between aluminum and copper. He says in his Conclusion 18 that "The loss and critical point are the same for copper and aluminum under the same conditions." That statement refers presumably to the same conditions of diameter, and not of conductivity, so that in practical work there may be a very marked difference between the use of the two metals, favorable to aluminum.

This paper marks another chapter in an interesting history which has been going on in the Institute TRANSACTIONS for the past ten years. To give a résumé for a moment—a dozen years or more ago, when large transformers of high voltage seemed to be something in the future, a high-voltage transformer giving 40,000 volts was made for the testing of insulators and for a general investigation into unknown regions of high voltage. In these tests, made at Pittsburg, some small wires were strung four or five inches apart, which showed a critical point, a very decided critical point, at which the wires began to give manifestations in three different ways, appealed to three different senses: to the eye by the corona and halo around the wire, manifested in the dark; to the ear by sound, and to the sense of smell by the odor of ozone, or something of that character. These three indications began to manifest themselves at a certain voltage which could be read very closely on the voltmeter, and the manifestations could be repeated in successive tests. Mr. Nunn was in Pittsburg about that time. He was then operating the oldest high-tension single-phase transmission, and was very much interested in these tests, and urged that tests of that kind be continued out at Telluride, offering the facilities of the power plant with the facilities of the apparatus and assistants and observers which were furnished from the east. A little later Mr. Mershon did the work which has been recorded in the Institute TRANSACTIONS, to which he has referred this evening. Professor Ryan became interested in these results. He wanted to get a scientific explanation, a law, and he carried on a very beautiful set of experiments which have been recorded in the papers which he has read and to which Mr. Mershon has referred.

Mr. Mershon has taken up the subject again, and has been able to draw some new conclusions. I think it is hardly worth while to add to the endorsements which have already been given to research work of this kind, which unites so closely the scientific, the engineering, and the commercial. We can hardly realize the difficulties which Mr. Mershon has encountered. He has alluded to them, with that little smile of disgust which he had a while ago, when he referred to the fact that he had to throw away some six months' tests, because something had been overlooked; but all of us who know Mr. Mershon and have known him for years back, realize his persistence. He does not stop at any ordinary obstacles.

**A. E. Kennelly:** While desiring to add my tribute to the great merit and value of the paper, I would like to ask a question about a point that seems difficult to understand. I refer to the effect of stranding the conductor upon the critical voltage. If I understand Figs. 39 and 42 correctly, the relation between critical voltage and outside diameter of the conductor is substantially the same for the solid wires and for the seven-strand wires. When, however, we come to 19-strand and 37-strand wires, there is a departure from the relation, and the critical voltage increases as though the diameter of the multiple-strand wire had been enlarged. In other words, do I understand the results correctly in deducing that the effect of stranding is only shown in 19-strand and 37-strand wires; and is not shown in seven-strand wires, which behave like solid conductors?

**Ralph D. Mershon:** Apparently the seven-strand conductor is equivalent to the solid, for the same extreme diameter, but No. 7 is 19-strand and No. 8 is 37-strand.

**A. E. Kennelly:** That is, the difference begins between seven strands and nineteen strands.

**Ralph D. Mershon:** Dr. Kennelly's understanding is in part correct and partly in error. The effect of stranding is shown in a seven-strand cable. The effective diameter of a seven-strand cable (that is, the diameter as regards critical point) is apparently that corresponding to the diameter of a solid conductor whose diameter is equal to the outside diameter of the seven-strand cable. The outside diameter of a seven-strand cable is greater than the outside diameter of a solid conductor *having the same carrying capacity*. The effect of stranding, therefore, in a seven-strand cable is to increase the effective diameter. When however, the cable has more than seven strands, the effective diameter is apparently greater than that of a solid conductor having the same diameter as the extreme outside diameter of the cable. In other words, the seven-strand cable appears to have an effective diameter greater than that of a conductor having the same carrying capacity, and equal to that of a solid conductor having a diameter equal to the extreme diameter of the seven-strand cable; while, with more than seven strands, not only is the effective diameter greater than that of a solid conductor having the same carrying capacity as the cable, but it is even greater than the extreme diameter of the cable. Why this should be the case I am unable to conjecture, unless it be that the smaller the strand used, the smoother and more polished the surface of the strand, because of the greater number of times it has been drawn through the die. Now, we know that the smoother the surface of a solid conductor, the higher is the critical point, and it may be that while the corrugations on the surface of the cable, due to stranding, are too large to amount to roughness, the smoother surface of the individual strands is effective in increasing the critical point.

Before replying to the other speakers I wish to ask Dr. Thomson with reference to Fig. 40, to see whether he has any suggestions to make in regard to that part of the subject.

**Elihu Thomson:** It is simply a question of the advisability of carrying to extremes the tests that are there shown. Quoting from the paper: "In Fig. 41 corresponding results have been obtained for different sizes of conductors at the same spacing. Here again, the residual differences do not differ widely, except at the high voltages where the loss is very sensitive to any change of condition, such as smoke, etc. On comparison also it will be seen that the residual differences are about the same in the two figures. Apparently, therefore, the increase of loss due to the increase of vapor in the atmosphere is the same for the same vapor product, no matter what the size of conductor or what the spacing between conductors. Why this should be the case, I am unable to conjecture, any more than I am able to arrive at any rational explanation of the relation between loss and vapor product." It seems to me it would be desirable that these tests be carried to extremes, to see whether the condition pointed out will hold through much wider ranges.

**W. L. Waters** (by letter): I think Mr. Mershon's paper on the losses in high-voltage overhead wires and insulators is the most important paper which has been presented to the Institute this year. Only those who have undertaken similar investigations realize the amount of work which is entailed in such an investigation. Mr. Mershon is greatly to be complimented on the perseverance and skill with which he has continued the investigations which he began twelve years ago.

There is just one point which I wish to discuss in connection with this paper, and that is the general question of insulator loss. Mr. Mershon finds that the insulator loss is considerably greater with wooden pins than with iron pins, and the explanation of this fact given by him does not altogether explain why we get much better results with some insulators with wooden pins than with iron pins. Mr. Mershon in his explanation considers the insulator as a condenser of infinite resistance in series with the resistance of the wooden pin. As a matter of fact, however, the insulator has not an infinite resistance, and under some conditions can have a comparatively low resistance. A more exact way would be to consider the insulator as a condenser with a considerable amount of leakage, in series with an ohmic resistance. There is leakage between the various parts of the insulator, both through the material of the insulator and over the surface. Assuming this state of affairs, the correct diagram is shown in the accompanying sketch, in which I have taken the system as consisting of a high ohmic resistance shunted at various points by condensers. We see from the vector diagram that the ohmic drop in the wooden pin is not in quadrature with the terminal voltage but makes a smaller angle, say 45 deg. or 60 deg., with it, consequently the voltage on the insulator is appreciably lowered by the use of the wooden pin, as shown in the vector diagram. The voltage from line to ground is $OE_1$ while the voltage on the insulator is $OE_2$, so we can understand why an insulator which will stand up satisfactorily with a wooden pin may not be able to stand up under the increased voltage to which it would be subjected when used with an iron pin. Of course,

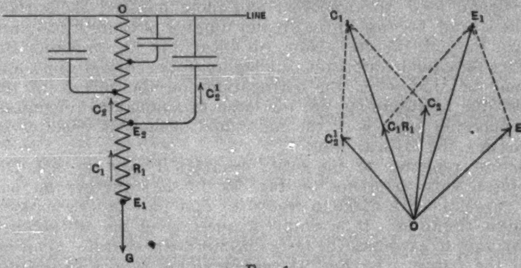

FIG. 1

it is impossible to say just how much the voltage would be reduced, in any individual case, without making measurements. Probably Mr. Mershon has figures from which he can calculate the reduction in voltage. The ohmic loss in the wooden pin is $C_1^2 R_1$ and the magnitude of this loss will decide whether there will be any trouble due to overheating of the pin; and the variable resistance of the pins on the line will account for the fact that some pins give trouble, due to burning, while others do not.

It will be seen from the above that the capacity and ohmic resistance of the insulator, and the ohmic resistance of the pin, together decide the success of the wooden pin in any particular case, and I would suggest that on account of the experience gained from Mr. Mershon's tests that Mr. Skinner add to his insulator-testing specifications a clause requiring measurement of the average ohmic resistance and electrostatic capacity of the insulators, and the ohmic resistance of the pins when of wood. These values could probably be determined without much trouble, when the insulators are tested in large numbers, and after we have a little more experience in regard to actual figures they would give us some idea as to the probable success of the insulators and pins.

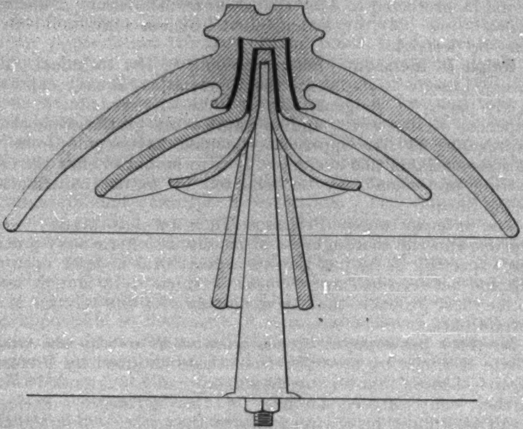

FIG. 1

**N. M. Snyder** (by letter): From observation and personal experience I concur with Mr. Mershon—especially in his Conclusions 13 and 14.

I also believe that the loss over insulators by moisture may be reduced materially by a change in design, and Conclusion 14, for example—the smoother the surface of a conductor the less the loss and the higher the critical point—seems to suggest a remedy. It is quite true, that a point or number of points on a highly charged body will dissipate a charge more quickly than if the body were entirely smooth; and by a series of tests we find that a charge will remain on the exterior rather than in the interior of a conductor.

Now, then, by so designing an insulator as to give the main feature the shape of a cone, as shown, to give a protection to the petticoat and pin from rain, the insulator would have the advantage that the surface would be comparatively free from points to radiate a discharge, and also that the inner petticoats would be protected to a certain extent from moisture, coal-smoke deposits, etc. By this arrangement I believe additional benefits may be derived.

**Ralph D. Mershon:** Before replying to the technical points raised, I desire to emphasize the appreciation, already expressed in my paper, of the generosity of those who contributed to the expenses of this work; and to express my gratification at the expressions of like appreciation which have come from the various speakers this evening. It is to be hoped that the engineering profession may be benefited by similar contributions in the future.

The interest which Professor Thomson has taken in this matter, and the thoroughness of his discussion are very gratifying, especially as he has thrown a great deal of light upon the relation between loss and "vapor product." In fact, it seems to me most probable that his explanation of this relation is the correct one.

Mr. Floy has brought up the question as to why the critical points obtained by me differ from those obtained by Professor Ryan. I think that his suggestion, especially if extended a little further, may largely account for this difference. Professor Ryan determined his critical points by the criterion of luminosity. There might have been, as suggested by Mr. Floy, an error in this method of determination, due to the personal equation, and to the conditions under which observations were made. But there is another possibility. Luminosity would require a certain definite amount of loss; that is, it would be necessary to be a certain distance above the critical point before luminosity would occur, and it may be that it is necessary to go quite appreciably beyond the critical point before the wires are luminous. There are two other considerations also which might, in part, account for the difference. One of these, touched upon by Dr. Steinmetz, and which I shall refer to again, is that Professor Ryan in his experiments undoubtedly realized the condition of a conductor having a uniformly smooth surface a great deal closer than it would be possible to realize this in a transmission line. The other is that Professor Ryan's experiments were made under such conditions as would give him as nearly uniform density of charge on the surface of the conductor as it is possible to obtain. Now, if instead of making the measurements between a conductor and a cylinder which surrounds it, they are made between two conductors, there is not a uniform distribution of charge on the surfaces of the two conductors. It is true that when the distance between the conductors is great as compared with their diameters, the charge is very nearly uniform, but, nevertheless, it is not exactly uniform, the density being very slightly greater on those portions of the conductors opposed to each other. This difference of charge means an increased rate of fall of potential, which increase, though very slight, would aid somewhat in lowering the critical point, and, therefore, in the discrepancy in results.

Dr. Steinmetz has said that the critical point as determined in my paper is not the true critical point, for the reason that the conductor and surrounding conditions are not absolutely uniform; that the first beginning of a brush discharge will be at some isolated point, some kink in the conductor, and that the voltage at which this occurs cannot be considered as the voltage where the breakdown strength of the system has been reached all over the conductor. The point Dr. Steinmetz raises is a very interesting example of the difference between engineering investigation and scientific investigation. The critical point I have determined in my paper is the engineering critical point of a transmission line, and is the critical point with which transmission engineers are concerned. The critical point of which Dr. Steinmetz speaks is the scientific critical point, and while it is very desirable to have it, after it has been obtained, it will be impossible to make use of it in transmission practice until there has been determined the corrective factor necessary to account for the " kinks " and " surrounding conditions " which will exist in practice. I quite agree with Dr. Steinmetz that it is very interesting and very desirable to have the scientific critical point, but I maintain that for transmission purposes the critical point as I have derived it is the one most immediately desirable and which we must have in any case. It is possible for us to get along without the scientific critical point, but the engineering critical point is absolutely necessary. Later on, I expect to continue this work, and at that time I shall endeavor to obtain the scientific critical point.

Dr. Steinmetz also takes exception to the method I have employed for determining the critical point; that is, by extending the lower limb of the loss curve and finding the point at which the upper limb departs from it. He says that both branches of the curve may theoretically be expected to go through the origin, and that if we had the equations of the lower branch in Fig. 38 and of the upper branch, the point of intersection would be the critical point. I do not see how these statements can be correct. The whole theory of critical voltage, as I understand it, is that the equation of the upper branch does not go through the origin; that the phenomena to which the upper branch is due begin more or less abruptly at the critical voltage. If this be the case, the critical point is the point at which the equation of the upper branch would cut the axis of voltage and is, therefore, in the curve formed by the combination of the upper and lower branches, the point of departure of the upper from the lower branch, and not, as stated by Dr. Steinmetz, the point of intersection of the equations of the upper and lower branches. Resort to the device suggested by Dr. Steinmetz, of plotting the logarithms of the ordinates, does not lead to satisfactory results. The upper portion of the curve obtained is not a straight line, so that if the endeavor is made to determine the critical point from this derived curve, it can be done only by resorting to the same method that I have employed; namely, that of determining the point of departure of the upper from the lower limb. In the derived curve, this method is more difficult of determination than in the original curve, because the rate of departure is less.

As regards the method of measurement used and the remarks made thereon by Mr. Thomas; I would say that while I have not used the particular method he mentions, I have made use of some methods of measurement involving a wattmeter in the high-voltage circuit, and found them extremely unsatisfactory. The chances for error due to electrostatic effects and other effects incident to the use of high voltage directly, are so great, especially when measuring losses as small as those concerned and at the very low power-factor at which they occur, that the use of instruments in the high-voltage circuit does not commend itself to me. On the other hand, having used the present method of measurement in the Telluride investigation, and having made use of it again in the Niagara work with entirely different apparatus, I have come to feel, as the result of such check measurements as could be made, and in view of the compatibility of the results obtained, that this method is absolutely reliable. In addition, it has to commend it the fact that one is working in a low-voltage circuit instead of a high-voltage one. I would say in reply to Mr. Thomas's question, that I have some data for losses which occur under rain conditions, but they are not definite enough to justify their presentation. During a rain storm or a snow storm the wattmeter continually varies with little jerky kicks. Mr. Thomas notes that the " vapor product " curves for the insulators are straight lines, while those for the loss between conductors are curved. As stated in the paper, the loss lines for the insulators would probably have been curves also if the readings had been carried to a higher vapor product. This was not done, because of the great expenditure of time that would be involved in waiting for weather conditions which would make possible measurements under the higher vapor product conditions. Mr. Thomas also refers to Professor Ryan's method of determining the critical point of a loss curve, and thinks that this might in part account for the discrepancy between my critical points and those of Professor Ryan. While there would, undoubtedly, be a discrepancy in the critical points determined in these two ways, this would not, I think, account for the discrepancy which exists, for the reason that the critical points finally given in Professor Ryan's paper were obtained not from loss curves—as I remember it he took no loss curves—but from his observations as to critical point as determined by luminosity.

Mr. Lincoln inquires as to the influence which the potential of the ground relative to the wires might have on loss, with particular reference to the losses on a three-phase circuit, as compared with those on a single-phase circuit. My measurements were all made on a single-phase circuit with the neutral grounded, so that I am unable to reply to Mr. Lincoln's question. I hope, however, to be able to supply this information later, as the three-phase loss is one of the matters which I have in mind for future investigation.

Replying to Mr. Scott's remarks, as to the bearing which these new critical points would have upon the conclusions arrived at in the paper which I wrote for presentation at the International Electrical Congress, I would say that the economic voltages of the International Electrical Congress paper are all well below the critical voltages of the present paper. I agree with Mr. Scott that in the use of higher voltages there may be a very marked difference in favor of aluminum, because of greater diameter of conductor corresponding to a line of given resistance.

**Ralph D. Mershon** (by letter): There is one point in Professor Thomson's discussion with which I do not agree, and which I feel sure is in error. He assumes, in discussing Conclusion 19, that the only insulator loss which could vary with frequency would be the hysteresis loss in the body of the insulator itself. I do not consider that this would be the case, and my attitude in regard to this matter will be clear from what follows.

The losses which, as I take it, occur in connection with an insulator, are as follows:

*a.* $I^2R$ loss through the substance of the insulator itself. This is the same sort of loss that would occur with direct current of the same effective voltage.

*b.* Hysteresis loss in the substance of the insulator itself, due to the variations of dielectric stress which occur with alternating current.

*c.* $I^2R$ loss in the film on the surface of the insulator, similar to that which would occur with direct current.

*d.* $I^2R$ loss in the film of the insulator due to the charging or condenser current taken by the insulator.

I think there can be no question that film losses or something equivalent thereto exist. The fact that insulator losses are different for different hygrometric conditions is proof of this, so that there will probably be no dispute as to the existence of the loss (*c*). That there should be a loss of the nature of (*d*) would appear from the following consideration. The several petticoats of the insulator and the different portions of these petticoats are undoubtedly at different potentials. The result is that between the various petticoats and portions of the same and between the petticoats and the insulator pin there is a condenser action; that is to say, the petticoats are analogous to the plates of condensers in series. To make the analogy more nearly exact, we must consider that between the condensers in series there are resistances because the charging current to the various portions of the petticoats must come to these portions through the resistance of the surface film of the insulator. Thus, the charging current to the insulator will cause $I^2R$ loss in the film on the surface of the insulator. Now, the magnitude of this charging current will depend upon the frequency, and the $I^2R$ loss due to this charging current will, therefore, depend upon the frequency, so that the insulator loss would be affected by frequency, even though the hysteretic loss, or loss (*b*), were zero. It was not loss (*b*) that I had in mind in Conclusion 19, but rather loss (*d*). I do not, therefore, agree with Professor Thomson that "if the insulator dielectric were free from all dielectric hysteresis, we should not expect Conclusion 19 to hold." Aside from the above theoretical consideration, that there is a loss of the nature of (*d*) is evidenced, I think, by the fact brought out in the paper that of the various insulators measured, some of the larger ones had the higher losses. We would expect that the larger the insulator, the smaller would be losses (*a*), (*b*) and (*c*), but that loss (*d*), if it exists, would be greater, since the charging current would increase with the size of the insulator, and the increase would be especially marked in insulators whose petticoats were approximately parallel to each other and to the pin. As pointed out in the paper, the measurements seem to bear out these two considerations, and it was because of this fact, and because it seemed to me that the loss in the substance of the insulator would be small, that the difference in the losses shown by the two curves in Fig. 32 was assumed as mainly due to loss (*d*). It has been suggested that this assumption is in error and that a large part of the difference in loss shown in Fig. 32 may be due to (*a*) or (*b*) or both of them.

Since the presentation of this paper, Mr. C. E. Skinner has very kindly had made for me some measurements bearing upon the ohmic resistance of an insulator similar to that to which Fig. 32 applies. He found that with a galvanometer connected in series with the insulator and with 500 volts direct current impressed upon the combination, no indication was obtained, although the galvanometer was such as would, on 500 volts, give an indication with 500,000 megohms in series with it. It would seem, therefore, that this definitely settles the question as to $I^2R$ loss in the substance of the insulator, to the effect that such loss is practically zero. As to the hysteresis loss, I am not in a position at this time to make any measurements bearing upon it, but expect to do so later. Meanwhile I have no reason to believe that any large portion of the difference in loss shown by the two curves in Fig. 32 is due to hysteresis.

I do not see the force of the comment made by Mr. Waters. Even if the insulator were a perfect condenser with no loss, a pin would increase the insulation strength, if it had sufficient resistance, and would also be a source of loss. The fact that the insulator is not a perfect condenser is shown by the measurements upon it. The loss is mainly, if not entirely, over the surface of the insulator. Possibly Mr. Waters has been misled in considering Fig. 37 by having overlooked the fact that, as stated in the paper, the pin, with which the curves of Fig. 37 were obtained, had to be wetted in order to make the measurements.

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# FUNDAMENTAL CONSIDERATIONS GOVERNING THE DESIGN OF TRANSMISSION-LINE STRUCTURES

BY D. R. SCHOLES

Before the work of designing a tower or pole for a given transmission line can proceed, a statement must be made setting forth the loads which the structure should be capable of withstanding. This statement is, in general, based on a forecast of the probable extreme weather conditions which may occur in the vicinity of the line, and also on a prediction as to what accidents will probably occur to the conductors of the line.

There is naturally considerable variation in forecasts of this sort and this variation is due primarily to a lack of accurate data regarding the various factors which enter into the case. The cost of a line is affected very largely by the figures which are selected to represent the probable extreme conditions, and the selection and application of these figures is, therefore, a matter of a good deal of importance. Unfortunately, data on this subject are very meagre, and a rational solution of a problem involving weather conditions and possible accidents is manifestly impracticable. It seems, therefore, that the best guide in selecting figures to represent the probable extreme load conditions is experience with existing transmission line structures and other structures similar to them.

During the last few years many members of the Institute have had occasion to investigate this subject, in preparing specifications for transmission lines. A discussion referring to experience with these lines and bringing out the ideas of each as to what load conditions should be provided for would be very beneficial. It is hoped that there will be such a discussion following this paper.

Figures must, in general, be selected to represent the forces which may come upon a transmission-line structure as a result of one or more of the following influences:

Wind.
Sleet.
Low temperature.
Accidents, as breaking of cables, etc.

It is also necessary to select a factor or factors of safety for use in connection with these figures, and a prediction must be made as to whether or not loads resulting from two or more of these causes are likely to occur at the same time. Considerations of cost often determine to what extent provision shall be made, in a given line, against such combinations of extreme conditions. In a very important line it may properly be considered desirable to provide strength against a combination of conditions likely to occur only once in a hundred years, whereas in a less important line the possibility of such a chance condition might, with equal propriety, be neglected.

*Wind pressure on structures.* The records of the weather bureau are available as an aid in estimating the maximum wind velocity to be expected in a given locality. The relation between wind velocity, however, as indicated by a government anemometer, and the actual pressure in pounds per square foot produced by a wind of that velocity on a cable or on the members of a tower, is by no means definitely known. In fact this relation is so uncertain that the most one can hope to gain from an examination of the weather reports is a general idea as to whether the winds occurring in a given locality are likely to be high or not. The anemometers of the weather bureau do not take account of sudden gusts of wind. The published velocities are not accurate, but must be corrected according to a correction table which may be obtained from the weather bureau.

The relation between wind velocity and the pressure produced by the wind on a plane surface normal to the direction of the wind is given by the formula,

$M = K V^2$, where
$M$ = pressure in lb. per sq. ft.,
$V$ = wind velocity in miles per hour, and
$K$ = constant.

Experiments in general indicate that the form of this equation is correct, but experimenters differ as to the proper value of $K$. The values given range from 0.0035 to 0.0048. According to tests by the weather bureau, $K = 0.004$, which is probably the most reliable figure there is for $K$.

Experiments indicate that, in general, higher pressures are to be expected at the top of a tower than near the ground, but little is known as to how the pressure is distributed. There is considerable doubt as to what should properly be considered the exposed area of a structure; it is certain, however, that both faces are not, in general, subject to the same pressure. It is usually considered that a reduction factor of 0.5 should be used in figuring the wind pressure per square foot of projected area of cylindrical surfaces. The wide use which has been given this factor is its principal recommendation.

The purpose of the foregoing remarks on wind pressure is to point out some of the reasons for uncertainty in wind pressure calculations. In view of these uncertainties, it seems necessary to turn to some empirical method for providing against loads due to wind pressure. In bridge work pressures of from 30 to 50 lb. per square foot are commonly assumed, and these pressures are used in connection with factors of safety of from 4 to 6. Structures built to withstand loads calculated in this way are found to be strong enough. How much too strong they are is a matter of conjecture. The usual transmission line cannot stand the expense of structures built to bridge specifications. Experience with bridges cannot, therefore, be of much help in the present connection.

Steel windmill towers have been in general use for about eighteen years. Such towers are built to withstand wind loads almost exclusively and their use is very widespread. It is known that the provision against wind loads in these structures is not excessive, for there are occasional failures. The windmill tower is, in general, similar to the towers used in transmission lines. The success of a given design of windmill tower depends on what might be called the integrated experience of all the users of towers of such design. Competition has led builders to reduce their weight to a minimum. It is probable, therefore, that a windmill tower of standard design which is widely used has just about enough strength to resist the highest winds, tornadoes excepted, and it would appear that a study of such a windmill tower will probably give the best data available for use in connection with transmission line structures.

An examination of a standard design of windmill tower, of which many thousands are in use, shows that such tower will actually fail under loads calculated on the basis of wind pressures of from 40 to 50 lb. per sq. ft. The tower referred to is of square pyramidal form, and in the calculations it is assumed that the wind is blowing at right angles to one side, and both faces of the tower are considered equally exposed.

It appears, therefore, that it would be good practice in transmission line construction to specify that the poles or towers should, in addition to their other properties, have strength to resist loads on their members due to a wind pressure of 40 lb. per square foot, with a factor of safety of from 1.5 to 2, based on actual test. Such a structure would be suitable for locations where the winds are high; in other locations these figures would be reduced by judgment, aided by a consultation of the weather reports and other such data.

*Factor of safety.* A few remarks regarding factor of safety may be proper at this point. The factor of safety used in connection with the design of a given piece of engineering apparatus, is, in a sense, a measure of the uncertainty attending the making of calculations of the loads to be sustained or of the strength of the structure under consideration. In designing a complicated structure to sustain a complex system of loads, it would be natural and proper to allow a large factor of safety, particularly if the structure were such that it could not be tested to destruction to check all calculations and methods. On the other hand, a smaller factor of safety would be equally safe in connection with a simple structure to sustain certain definite loads, the actual ultimate strength of the structure having been determined by testing it to destruction.

The structures ordinarily used in transmission lines are simple. They are usually built in large numbers from standard designs. It is proper, therefore, that the design for such a structure should be carefully investigated and that specimen structures should be tested in such way as to remove all doubt as to their ability to withstand the loads for which they are intended. And, notwithstanding the fact that calculations of wind pressure are uncertain, experience with windmill towers removes, to a large extent, the uncertainty which would otherwise surround the figure 40 lb. per square foot which has been suggested.

*Wind pressure on cables.* The opinion is commonly held that, in providing against wind pressure on a surface such as that of a long span transmission line cable, it is not necessary to allow for as high a pressure as is necessary for a surface extending through smaller linear distances. Data on this subject are, as yet, very indefinite, and there is great need of specific figures for the pressure experienced on the cables of a transmission line. The following experiment is suggested as a means of securing such data.

The experimental apparatus would consist of a typical transmission line span of from 500 to 1000 ft., erected as near as possible to a weather bureau station. The cable would be fixed to the tower at one end and would pass over a pulley at its other end and be secured to a weight, this weight serving to maintain a uniform tension in the cable at all times. The position of the weight would be recorded at all times by means of a pencil and moving drum. Continuous records of temperature and wind velocity are made in the weather bureau stations. An analysis of the three records; namely, those of temperature, wind velocity, and the length of the cable in the span, would give data from which the wind pressure in pounds per square foot of projected area of the cable could be calculated. It would also be desirable to have a continuous record of the direction of wind, and this record could be readily obtained.

Records from such apparatus extending over a period of a year or more would be of much interest. It is to be observed that the readings would furnish a means of checking the coefficient of expansion of the cable. Data obtained in this way would have direct relation with the weather bureau reports, and most questions as to methods of calculation of pressure on conductors would thus be eliminated.

In the absence of specific data relating to wind pressures on the cables of long spans, it seems unsafe to assume a pressure of less than 30 lb. per sq. ft. for localities where the winds are known to be high. The figure 30 lb. per sq. ft. is commonly used in bridge calculations for surfaces extending through horizontal distances of 60 ft. or more. It seems that a factor of safety of 2 should be used in connection with this pressure, so that the conductor will not be stressed beyond its elastic limit, under extreme conditions.

*Sleet.* Destructive sleet storms occur in the eastern part of the United States at least as far south as Atlanta. During the past winter, a sleet storm occurred in the region of Chicago after which a coating of ice over half an inch thick was observed on conductors of various sizes. In many cases the thickness of ice at the center of the span was much greater than at the insulators, due to the tendency of the water in the sleet to run down to the lowest point while freezing. The sleet formed during this storm was practically solid ice, and it remained on the conductors for several days. In view of observations made after this storm, it is the writer's opinion that, for localities where sleet is known to form, provision should be made against a coating of ice on the cables at least one half inch thick, in combination with a factor of safety of not less than 2 based on the ultimate strength of the conductor.

There is much discussion as to whether the safety of a line demands that provision be made against sleet, low temperature, and high wind all occurring at the same time. If the sleet forms at all, it is certainly possible that it will remain on the wires several days. And if it remains on the wires several days it is certainly entirely within the range of possibility that high wind or low temperature or both will occur before it melts off. Whether or not provision should be made against a combination of these three extreme conditions becomes, therefore, entirely a question of how much the owners of the line are willing to pay for immunity from interruptions of service due to these causes. These are matters to be settled between the engineer and the owner of the line.

*Accidents, as breaking of wires, etc.* In providing mechanical strength in the line to resist loads due to accidents to the cables, there are two well known plans which may be followed. In the one all structures are given the same strength, each having strength to withstand the loads due to accidents which it is contemplated may occur in any span; in the other plan, two kinds of structures are used—a standard structure intended to support loads transverse to the line only, and a heavy structure having strength against the breaking strength of all the cables. These heavy structures are distributed along the line at intervals of a mile or so. The first mentioned type of construction is best adapted for lines having relatively small conductors, while the second type is favorable where the conductors are heavy.

In designing a line of the first mentioned type it is usual to assume that any two conductors may break in a given span due to the formation of an arc between them, and that the tower or pole should be capable of withstanding the loads so developed without damage to itself. Provision is not, in general, made for the simultaneous occurrence of such breakage and high wind or sleet. It would seem, however, that in such cases the towers might better be designed to withstand wind loads transverse to the line in addition to the loads due to the breakage of any two conductors, since arcing is more likely to occur in a high wind than at other times.

It is believed that the factor of safety used in connection with the loads due to breakage of conductors should be greater in the case of suspension type insulators than with pin insulators. When a conductor supported by suspension insulators breaks, it will suddenly move away from the point of breakage and will be brought to a sudden stop when the insulator comes into line with the cable. The movement will occur, in decreasing amount, all along the line, or until a strain insulator is reached. This sudden application of load and the attending inertia effect will subject the cross arm to a greater force than the tension which existed in the cable before it broke. It is suggested that cross arms be tested to loads equal to 1.25 times the elastic limit of the conductor for pin insulators and 1.5 times the elastic limit of the conductor for suspension insulators.

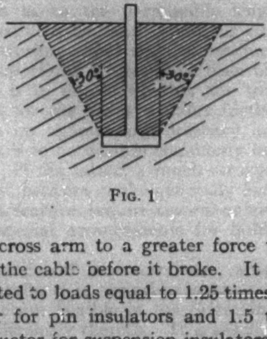

FIG. 1

*Foundations*. It is a usual assumption that the resistance to uplift offered by a foundation is equal to the weight of the foundation plus the weight of earth contained in the frustum indicated in Fig. 1, the angle of inclination of the sides of the frustum being 30°. The results obtained by this method agree quite closely with practice in anchors for windmill towers. In addition to resisting uplift, the foundation must, in general, have strength against horizontal forces at the ground line. The variety of designs of foundations is so great as to make a discussion of them impossible within the limits of this paper. It is suggested that, in developing the design of a foundation for a given line, tests should be made to determine the holding power, density, etc., of the soil of the locality so that the strength of the foundation will be known as accurately as the strengths of the other parts of the line.

## DISCUSSION ON "FUNDAMENTAL CONSIDERATIONS GOVERNING THE DESIGN OF TRANSMISSION LINE STRUCTURES."

### ATLANTIC CITY, N. J., JUNE 30, 1908

**N. J. Neall** (by letter): It may properly be said of a transmission line structure that factors of safety are both necessary and expensive. It is naturally desirable, therefore, so to shape the design and so to adjust it to its operating requirements as to secure a maximum of service with a minimum of outlay.

There are two factors of safety that must be considered: 1. That relating to the transmission line conductors directly. 2. That of the tower itself as an independent structure. These will be discussed as follows:

1. Factors of safety relating to transmission line conductors. Once the amount of power to be delivered has been determined, together with the location of definite geographical points of distribution, a fundamental size of transmission wire can be deduced to carry the load economically. This should then enable a decision as to the permissible length of maximum span and an adjustment between conductor size, span, and cost of support (substituting other sizes of conductor if necessary) until the best proportions of cost have been obtained.

The next step is to decide whether the tower is merely to act as a support for the wires without further responsibility, or to hold them up against any ordinary accident; in other words, whether it is to be what is commonly known as a " dead end " structure. If the latter, a much stronger pin support is required and may, because of the generally low natural limit of strength of such a feature, require several or more such supports in tandem and special arrangements for holding the wires to the supports.

2. Inherent structural characteristics affecting factors of safety. Theoretically it is desirable to have a tower or transmission line structure flexible in the direction of the line, and inflexible perpendicularly thereto. It is assumed that any wind blowing parallel to the line does it no harm, while a high wind perpendicular to the line is a serious feature; in other words, the tower must be able to resist being blown over. This consideration immediately affects the shape and size of the tower, to which, in turn, such items as wind pressure per square foot, form of anchorage, nature of soil, etc., add their quota of requirements.

For such a structure pure and simple, the requirements of endurance are obvious and of little concern to the electrical engineer, save that the character of the design will permit of the special loads being applied without any impairment of the structure as such.

It is but a step, then, to combine these two elements; in the usual specification the loads brought on the tower by the transmission wires are the only ones specified. It is here that I think there is much room for improvement over present practice.

When it is borne in mind that both the tower itself and all conductors are simultaneously affected by any of the usual elemental conditions considered in this connection, such as heat, cold, wind, dead weight, ice or sleet, etc., and since moreover it is found in usual requirements that a safe length of span to stand minimum temperature, with ice or sleet, and wind blowing simultaneously at a maximum velocity determined by local observation to be applicable to this case, is taken at the condition of maximum strain on the conductor, it becomes clear that the only true criterion of suitability of a structure is to test it preliminarily for design in such a way as to imitate as closely as possible just those strains that come upon a tower in service. The two extremes usually taken are the one for minimum temperature, sleet, and relatively low velocity of wind; and the other, maximum temperature and highest wind velocity. With reference to the tower, the former may be considered for the present as less serious than the latter, principally since dead weight is such a large factor in the cold, and sleet condition and structures for transmission lines are thought to carry this more easily than the maximum wind condition.

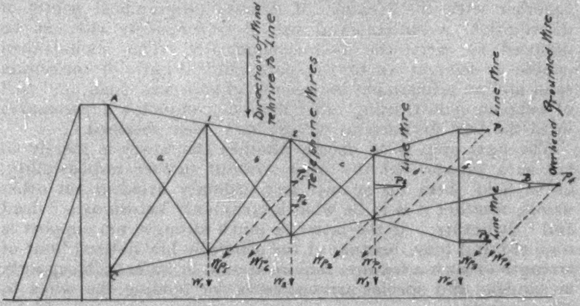

FIG. 1.—Loads on tower for maximum temperature and minimum wind velocity.

In order to test the tower, once the line details have been preliminarily worked out, two methods are possible.

First, the tower is mounted on a concrete or other firm foundation and loads applied at various points by means of cables suitably equipped with a dynamometer, or, more conveniently, as follows.

Secondly, the tower fastened horizontally. Let *A B C* represent the structure fastened rigidly to a strong support. Then by calculation the resultant direction and amount of dead weight of wire and wind for the wire when two adjacent spans are in equilibrium can be determined, and the load corresponding thereto can be suitably applied to the tower, as shown by *Wp* 1, *Wp* 2, *Wp* 3, etc. This is the only load brought on the tower by the conductors for this condition of the weather, viz., maximum wind and maximum temperature.

By a proper calculation the total stress on the tower can be determined. For the purposes of this test, these loads are best applied at the girts 1, 2, 3, etc., as shown on diagram, and are indicated by $W_1$, $W_2$, etc. For the horizontal position the dead weight of the tower must be taken into account, and $W_1$, $W_2$, etc., represent the additional amount to equal the calculated values.

From this it is obvious that any of the conditions applying to tower operation can be properly investigated. For example, one test can be made of "dead end" structures, where the strain in the wire (much in excess of that used as its dead weight and wind exposure pressure per support for towers under the usual service requirements) is appropriately applied at the insulator pins.

Horizontal strength or resistance to twisting from one or more broken wires (known commonly as torsional strength) under any given condition can be easily worked out.

The maximum amount of load which should be applied under these circumstances should depend on the given conditions of the test. I think that an all-round factor of safety of 2 will well meet most commercial requirements, particularly if the test is made for a condition of maximum weather effect.

It is easy to argue that if minimum temperature, sleet, and wind are the worst for the wire and that as a matter of design this strain is made equal to the elastic limit of the conductor, we have roughly a factor of safety of 2 against breakage, coupled with a relatively remote possibility of occurrence. The same basis of selection might apply to the structure as well. The usual specification for a given pull at the insulator pins is only a quasi-wire strain; it is practically a test of the strength of the tower built up to the pin strength as a basis.

Structurally, the insulator pin strength is the weak point of the ensemble; an average pin strength of approximately 1500 lb. to 2000 lb. does not give much leeway in the use of a single pin for dead-end work, nor for a large factor of safety. It is surprising, however, how much can be obtained from a given weight of material if properly disposed.

Some time ago I tested two towers in the manner described, the only difference of importance being the method of holding the diagonal rods *a*, *b*, *c*, and so forth. The builder of the tower employed what I have termed a button and buttonhole method of attachment for the diagonals to the girt. The rod was provided with a button-like end, and the girt was cut button-hole-wise to receive this. In the second tower the diagonals ended in loops and were held by bolts, washers, and nuts to the girts or corner parts respectively, as happened to be. The total weights were not sensibly changed, and yet the latter arrangement showed itself much the stronger.

Strangely enough, the first tower had been successfully tested according to specifications by heavy loads applied to the pins when in an upright position. The second method showed easily how unsatisfactory the other might be as an indication of all-round strength.

The result of all this is a better appreciation of the behavior of the tower under service conditions, and leads directly to the conclusion that in this wise purchasers of towers can obtain a high degree of economy of tower material for a given amount of money.

In these discussions before the Institute cost is more than likely to be treated academically. In no place is it more critical, however, than in the problem of selection of a transmission line support; in fact, despite the many advantages of tower construction over its predecessor—the wood-pole line—the first cost of a metal tower line constantly tends above the wood pole, and of this the tower alone plays a large part, and increasingly so as the factor of safety increases.

With careful selection of design, such a line construction can be kept within reasonable limits; but to this end it is necessary to emphasize the point that not all towers should be dead-end towers; in fact, comparatively few may be so, and the remainder must be something less than this.

Since continuity of service is the final measure of success, in such a case it seems to me that any detail of construction used in this connection should be tested *destructively* for type before acceptance. In my judgment the test herein described is no more burdensome on the tower than standard arcing-over tests, etc., now employed for insulators. Each seeks to determine the ultimate strength of the respective detail under its known possibilities of service.

**Ralph Bennett** (by letter): The available data on existing transmission lines must necessarily be of a negative character, for a line is built to stand. It does so; therefore it is satisfactory. The margin of security in such a case is difficult, if not impossible, of determination.

A factor of safety of 2 against the greatest combination of known and assumed strains seems inadequate unless the strains themselves contain a large excess allowance. The following uncalculated strains occur to a greater or less extent in every tower: 1. Irregular loading due to settlement of footings and to uneven cable tension. 2. Load due to vertical and horizontal angles too slight to warrant special towers. 3. The results of line and side guying. 4. The racking effect of unequal adjacent spans under temperature changes.

A factor of safety of 2.5 against the extreme load would give a margin between the total calculated loading and the elastic limit of 25% of the load. This should be sufficient to produce a line which would stand in any weather. It is not sufficient to build a line which would just fail under the extreme weather condition which can be expected. A line important enough to warrant steel or concrete towers will warrant sufficient expense to make it secure.

The Kern River Transmission of the Edison Electric Company was designed in 1905 and erected in 1906-7. It has now been in active service slightly over 12 months. Part of the towers have had wire on them for two winters.

The essential features are as follows:

| | |
|---|---|
| Standard span | 700 ft. |
| Size of cable | 4-0 copper, 7 strand |
| No. of cables | 9 |
| Average height above earth | 57 ft. |
| Base at earth | 12 by 12 |
| Depth of footing | 6 ft. 6 in. extreme. |
| Diameter of footing plate | 24 in. |
| Type of tower | 4 post |
| Tower bracing | tension rods |
| Total wind load on wire (22.5 lb.) | 6300 lb. |
| Dead load due to wire | 4050 lb. |
| Extreme longitudinal load (due to to failure of one wire) | 3000 lb. |

No sleet or snow; no temperature below 20° fahr.; maximum temperature 130° fahr.

At this writing the only difficulty experienced with the line has been due to eagles, which roost on the lower cross-arm between the insulator and the upright. In flapping their wings preparatory to flight they cause a short-circuit from the wire to the structure. In a few cases this has burned the cable off. No tower failures have resulted from this or any other cause. Most of the line has as yet but six cables, and as a consequence there are as yet no data on the effect of side winds. But the absence of three cables renders the effect of cable failures and guying much more serious than it will be in the completed line.

Before issuing the tower and wire specifications an experimental span of 1000 ft. of a single 19 strand 00 copper cable was observed at intervals during about a year. Its performance in respect to temperature change was very closely in accordance with calculated values. The methods of measuring wind proved to be so crude that the results were indeterminate. Other observations were made with rods of various shapes projected from the side of interurban cars. These results were also only approximate. The average of a large number of observations indicated that the pressure on round rods was less than six-tenths of that on thin flat rods of the same projected area for any velocity up to 30 miles per hr.

The method of figuring footings given by Mr. Scholes is based on the angle of repose of loose sand. This can scarcely apply in firm or sticky or flowing soils. Most tower footings are in soils which are at least self-supporting. Such materials as gravel and stiff, dry clay are very slow in recovering their original firmness, even if tamped thoroughly. Meanwhile a footing placed in a straight-sided hole is liable to lift the loose dirt out along the line of disturbance with a much less load than that calculated by any formula based on an assumed cleavage line. If, however, the earth is firm enough to permit of enlarging the hole at the bottom so that the sides overhang the footing plate, the completed footing may hold more than the calculated amount, for the angle of repose of such a soil in a massive body such as that surrounding the foundation may be much greater than that of sand.

In setting guy-plates no lineman would think of so placing them as to bring the strain against the disturbed earth. In ordinary pole-line construction the disturbed earth is subjected to direct compression only, yet the only valid reason for the deep holes commonly used is to bring the point of maximum loading on this earth so low that it will be held from flowing under the pressure by the firm earth surrounding it.

Where economy would demand the minimum cost to such an extreme as to render the skimping of footings necessary, would not the use of guyed towers instead of the self-supporting types result in a more reliable construction? Such towers would be much lighter; they would occupy less room at the base; they could be so constructed that the longitudinal guys would also take the side strains; and all earth plates would be against firm, undisturbed earth. Since the variation in load with length of span affects the wind load as much as the dead load, and as any tower which will stand the stress of erection will stand the dead load, the towers could be adjusted to their loads by changing the number or size of the guy wires. The total weight would be low, as would the erection cost. The parts would be stiff enough to stand erection strains without the elaborate precautions taken on one or more of the lines recently noted in the technical press. It seems almost a truism to say that in construction of this character the parts should be few and rugged so that the money saved on shop cost need not be lost in the field in the handling of fragile members or the locating of a large number of small pieces.

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# THE TESTING OF HIGH-VOLTAGE LINE INSULATORS

BY C. E. SKINNER

The specification herein proposed as standard for the testing of high-voltage line insulators was written at the request of the chairman of the High Tension Transmission Committee in order to bring this matter before the Institute for discussion. It is not presented as representing the writer's personal opinion so much as an endeavor to harmonize information which he has obtained from various sources with the view of producing such a specification. Quite a large number of porcelain manufacturers and others interested in the testing and use of high-voltage porcelain line insulators in this country and in various parts of Europe have been consulted, and the information received is embodied as far as possible in the proposed specifications. It is fully appreciated that differences of opinion may exist on any point which is incorporated in such a specification. The fact that such differences do exist, and that tests are so different in different places, seems to the writer to be ample justification for the attempt at a specification which can be used by all as a standard of reference.

At the present time it is almost impossible for one familiar with a certain method of testing to base any judgment whatever as to the bearing of results obtained by some one else who uses a different method. If, after thorough discussion, and any revision which may be found essential, a specification is produced which will allow direct comparisons to be made of the performance of insulators of different types tested in various places and at different times, the object of the specification will have been in part accomplished. If a specification is evolved which can be accepted as a standard performance specification for line insulators in general, the uncertainty regarding comparisons of tests at various places and the widely varying requirements now insisted upon for conditions which are practically the same, will have been eliminated.

The specification naturally divides itself into three general parts. The requirements of routine tests are placed first, as it is considered that any tests of a routine nature which are required on insulators for the acceptance of any lot should naturally form a part of the tests made to determine the limitations of design.

The question of routine inspection for mechanical flaws and other defects is difficult to outline definitely, as a complete description of all points which might constitute cause for rejection would make the specification unduly long and complicated, and it is therefore usually considered better to leave this to the judgment of the inspector.

Some difference of opinion has been expressed as to whether the dielectric test on each individual part of insulators made up of parts should be included in the routine test instead of in the design test. It is the writer's understanding that such tests are invariably made by the porcelain manufacturers for their own information, whether specified as a part of the routine test or not, and it would therefore seem that there should be no very great objection to their being included in the routine test.

It is possible that in some designs the voltage tests specified cannot be met by certain shells which are used next to the pin for the purpose of increasing the dielectric strength when the other parts of the insulator are wet, due to the short surface distance. If the surface distance on the short shell is so small that this test cannot be reached, it is probable that the object of inserting the short shell is in some measure defeated in the particular design. It might be possible to substitute a fixed test for each individual part of a shell independent of the voltage on which the insulator is to be used, as it is difficult if not impossible to get porcelain to stand tests of above 60,000 to 70,000 volts, regardless of the thickness. The better material in the thinner shells gives results equal to the poorer material in the thicker shells, due to shrinkage cracks and other defects which it is ordinarily impossible to eliminate in thick porcelain. The provision to exclude insulators which show excessive local heating is inserted for the reason that those familiar with such tests may at times be perfectly sure that an insulator is unsatisfactory even though it is not punctured. The term "localized discharge" as used does not mean the discharge which occurs uniformly around the insulator at the point of contact, but a discharge at some point on the surface. Such discharge sometimes indicating a spongy material which will eventually give trouble.

Under design tests the amount of pull to be applied to the insulators is not specified for the reason that the strength must necessarily depend on the particular design, and the figures to be inserted of course should be agreed upon in each case between the manufacturer and the user.

The rate of precipitation specified in the rain test is probably greater than will ever be experienced except in very excessive storms, and even then only for a very limited time. The rate specified is less than that used as standard in some parts of Europe. A fairly wide limit of variation in rate is allowed, partly on account of the great difficulty in securing a perfectly definite and uniform rate, and partly from the belief—borne out by rather limited tests—that little difference in the results of tests will be obtained between the limits specified. It is desirable in the discussion of this paper that as much information as possible be brought out relatively to the best possible method of obtaining a satisfactory spray.

The requirement that the insulator shall be tested with the pin at an angle rather than to attempt an angular rainfall is given for the reason that a satisfactory method has not yet come to the writer's attention for the obtaining and maintaining of a satisfactory angular rainfall, under the conditions which usually obtain where insulators are to be tested. It is far easier to incline the insulator and use a vertical precipitation, and it is considered far more probable that results can be repeated than by providing for an inclined precipitation.

The use of a rain gauge for determining the rate of precipitation is specified, as the writer has found it nearly impossible to get the rate of precipitation by measuring the flow of water through the supply pipe, which is frequently done. The diameter is limited to three inches for the reason that a larger gauge would disturb the distribution of the spray to some extent. The type of rain gauge illustrated herewith is suggested as convenient and as having been found satisfactory in tests where it has been used. The diameter of the funnel is so chosen that the precipitation for any elapsed time measured in cubic centimeters and divided by 100, gives the rate of precipitation in inches for that elapsed time. By means of the valve at the bottom the water may be run into a standard chemical burette, and quite accurate measurements made. In use the rain gauge is inserted upside-down into the spray, and then quickly turned to the upright position when the location to be measured is reached. A suitable card or other covering is then quickly placed over the top at the end of the elapsed time. It would, of course, be easy to provide a lid which could be opened and closed, in place of the method specified.

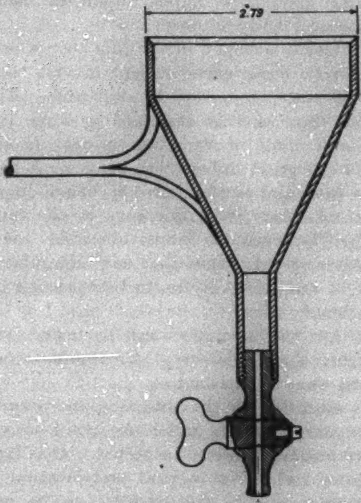

Fig. 1—Special rain gauge

The writer would lay special emphasis on the importance of the dew test as probably determining the most severe condition which the insulator will ever be called upon to meet in practice. Also the fact that such a test is more nearly capable of exact repetition than any precipitation test. Furthermore, in such a test the moisture on the surface of the insulator must be perfectly clean water if the insulator itself is clean, and therefore is more like natural rainwater and eliminates any possibility of variations due to the quality of the water used.

## PROPOSED STANDARD SPECIFICATIONS FOR THE TESTING OF HIGH-VOLTAGE LINE INSULATORS

*General.* This specification is intended to provide a standard method of making tests on porcelain insulators or their equivalent which may be designed for use on transmission systems of 6000 volts or above. The specification is intended to provide a means of determining the performance of any insulator, and is not intended to restrict design in any way whatsoever. The specification is divided into three parts as follows:

1. *Routine tests*, or tests to be made on each individual insulator, to show whether or not workmanship, materials, and dielectric strength are up to the required standard.
2. *Design tests*, or tests to show the limitations of a design under a specific set of test conditions.
3. *Methods of testing*. The methods to be followed in making the various tests specified, are separated from the body of the specification as a matter of convenience for reference.

### 1. ROUTINE TESTS

*a. Inspection.* Each insulator shall be inspected to see that it is reasonably free from mechanical flaws, defects of glazing and cementing, chipping, etc. Those parts of the insulator which are to be fitted to caps, pins or other fastening devices shall be sufficiently close to designed dimensions to insure first class work in assembling and mounting. The general over-all dimensions shall not vary more than plus or minus 5 per cent. from the designed size.

*b. Dielectric tests.* When tested dry each shell of insulators of the cemented type and each unit of insulators made up of units, shall withstand for a period of 5 minutes three times its proportion of the line voltage, based on the total number of shells or units of which the insulator is composed. (For example, each shell of a four-part insulator shall withstand ¾ times the normal line voltage on which the insulator is to be used, for a period of five minutes.)

When tested dry each completed insulator shall withstand for a period of five minutes 2.5 times the line voltage on which it is to be used.

If any shell or any insulator shows excessive localized discharge without puncture, the test on same may be continued for two additional periods of five minutes each. Excessive local heating or excessive localized discharge shall, if continued, be considered a failure.

Insulators not to exceed 5 per cent. of any lot shall be tested for flash-over by raising the voltage gradually, or by steps of not more than 5 per cent., until flash-over occurs. If there is failure by puncture of more than one-half of those so tested, the flash-over test may be required on all insulators of the lot on order.

### 2. DESIGN TESTS

Tests to determine the limitations of any particular design are to be made on a few insulators, not more than 5 per cent. of any particular lot on order.

a. *Mechanical tests.* Insulators mounted on pins shall withstand a side pull exerted on the tie groove at right angles to the axis of the pin, of . . . pounds. Cemented insulators and insulators made up of units shall withstand a direct pull along the axis of the pin, or equivalent, of . . . pounds the force being exerted between the crossarm and line fastenings.

b. *Routine tests.* Insulators must successfully withstand tests under the heading of routine tests.

c. *Rain tests.* In addition to the routine dielectric tests, the insulators shall withstand the following dielectric test when subjected to artificial rain. With a vertical precipitation of not less than 0.3 in. per minute and not more than 0.4 in. per minute, the insulator in normal position mounted on a crossarm or its equivalent, with pin with which it is to be used, the complete insulator shall withstand for five minutes 1.5 times the normal voltage of the line on which it is to be used. With the same rate of precipitation and with the crossarm so turned that both the crossarm and the insulator pin are at an angle of 45° to the vertical, the complete insulator shall withstand for five minutes 1.25 times the normal voltage of the line on which it is to be used

d. *Dew test.* With the insulator cooled to 0° cent., or below, and then placed in a moist atmosphere of 30° to 40° cent., it shall withstand 1.25 times the normal line voltage after the insulator has become thoroughly covered over its entire surface by the condensation of moisture from the atmosphere.

### 3. METHODS OF MAKING TESTS

a. *Mechanical test.* The strength test of the insulator may be made by any suitable means of obtaining the specified pull. For this test pin insulators should be mounted on the pin with which they are to be used in practice, and a heavy copper wire or cable looped in the tie groove in such a way that there will be no injury exceeding that which would occur from the application of the standing tie. Insulators of other types shall be tested by having the pull exerted between the mounting intended for the crossarm and the line wire.

b. *Dielectric tests. Dry test.* The surface of the insulator shall be clean. The test on pin type insulators shall be made by placing the insulator upsidedown in a pan of water to a depth just sufficient to cover the tie groove or equivalent. This pan with water forming one testing terminal should be as small in diameter as possible and so arranged that the striking distance over the surface of the insulator is not reduced. Water shall be placed in the pin-hole of the insulator, covering that portion of the insulator which would come in contact with the pin or equivalent. When insulators have metal thimbles placed in the pin-hole or are mounted complete with metal pins, the thimbles or pins may be used in place of the water in the pin-hole. Connection to the water in the pin-hole forming the other testing terminal shall be made by means of any suitable metallic conductor, which must be so placed that it is central with the pin-hole and extends far enough above the insulator so that it will not shorten the striking distance from the wire groove to this conductor. In testing the shells of insulators made up of concentric shells, tests shall be made from a pan of water in which the insulator is placed upside-down as one terminal, to water placed inside the shell as the other terminal, the depth of water in the pan and in the shell being so arranged as to cover that part of the insulator which will be in contact with the cementing material. In testing units of insulators made up of units, the testing terminals shall consist of the metal mountings or their equivalent, with which the insulators are to be used in practice.

*Rain test.* The rain test shall be made by mounting the insulator on a metal pin or equivalent so arranged that it may be placed either vertical or at an angle of 45° to the vertical. Clean water shall be used and the precipitation shall be such that the water falls in a fine spray and in practically a vertical direction and at a rate of from 0.2 in. to 0.3 in. per minute, over the area formed by the vertical projection of the insulator. The rate of precipitation shall be obtained by the use of a suitable rain gauge of not more than 3 in. in diameter.

*Frequencies.* Dielectric tests shall be made at the standard frequencies of either 25 or 60 cycles per second. Any frequency between 25 and 60 cycles will be considered as meeting the specification. Lower or higher frequencies will be considered as special.

*Voltage control.* When only a very limited number of insulators are tested in parallel, the test voltage may be taken from a constant potential source and applied directly or it may be raised to the required value gradually. When a considerable number of insulators are tested together, the test voltage shall be raised to the required value smoothly and without sudden large increments and then applied for the prescribed interval. Flash-over tests and other tests requiring variation of voltage shall be made by raising the voltage to the required value smoothly and without sudden large increments.

## DISCUSSION ON "THE TESTING OF HIGH-VOLTAGE LINE INSULATORS." ATLANTIC CITY, N. J., JUNE 30, 1908

**Percy H. Thomas:** The testing of a high-voltage insulator by application of voltage from a spark-gap or other high-frequency discharge has an extremely important bearing on the type of insulator. A four-part insulator or a three-part insulator, in fact any large insulator, has its resisting power made up of a number of elements all practically in series. The possibility of the concentration of potential on certain parts of these insulators is well recognized. This condition is recognized as greatly reducing the breakdown voltage of an arrester. The feature I wish to bring out is that with very high frequencies this concentration effect is enormously multiplied. I believe that a careful study of this matter will result in some modification of insulator design.

I ask Mr. Skinner if it is worth considering that there will be a difference in local heating, according to the frequency of the test current; for example, a 133-cycle test might show local heating which would not show on a 25-cycle test. Any local heating in a specific insulator is a very important item, as it indicates an inside weakness.

**Ralph D. Mershon:** Mr. Skinner's paper interests me not so much because it suggests specifications for an insulator but because it recommends certain definite methods of test. There is one recommendation especially with which I heartily concur; that is, make rain tests by using, in all cases, a vertical spray and placing the insulator at a specified angle, instead of endeavoring to imitate rain conditions as regards the angle of precipitation.

Rain conditions are indefinite and variable, so that any assumptions made in regard to them must necessarily cover only one of many conditions. The best that can be done is to assume a maximum rate of uniform precipitation at a definite angle. We know, with a fair degree of accuracy, the maximum rate which will not be exceeded in practice. The angle of precipitation may, however, vary from approximately zero degrees with the horizontal, to 90 degrees. It is usual to assume 45 degrees as a fair compromise. But having made thes assumptions, which can not represent all actual conditions, we are unable accurately and conveniently to produce them. It is extremely difficult to get a water spray to fall at any definite angle, other than 90 degrees with the horizontal, and with uniform precipitation. The result is that flash-over tests made by different observers with different testing equipments, or even at different times by the same observer with the same equipment, are often most discordant.

It seems to me it would be much better to adopt a method of test which, whether it does or does not appear to represent very closely actual conditions, will serve as a criterion and will offer some chance of reproduction, approximately at least, at different times and with different observers. This will be accomplished if the spray be kept vertical and the insulator inclined, for there is a great deal better chance in that case of obtaining a uniform spray at a definite angle with respect to the insulator.

The present method of testing insulators for flash-over conditions under precipitation is very unsatisfactory, so far as repetition is concerned. I have lately made some experiments on a new type of insulator under what was supposed to be a precipitation of one inch in five minutes at an angle of 45°. About a week afterwards another observer made similar tests under as nearly as possible similar conditions, and obtained the same results. About three weeks afterwards the same man endeavored to repeat the results and could not get anywhere near the figures which had been obtained in the first place for flash-over under rain conditions. I have had similar experiences repeatedly and, as the result, have usually, when desiring to compare two insulators as regards flash-over, endeavored to test them together, either simultaneously or by keeping the spray the same and alternately substituting one insulator for the other. The latter is probably the safer method, as more likely resulting in the same precipitation in both cases.

I am disappointed that Mr. Skinner has not gone more fully into the question of the kind of spray nozzle for producing a uniform precipitation. It is difficult to get a nozzle which will give uniform distribution and do so continuously. It would be of great value if Mr. Skinner could tell us where or how to obtain a nozzle which would fulfil the requirements.

The rate of precipitation usually assumed is about one inch in five minutes. The maximum rate of precipitation of which the United States Weather Bureau has any record is less than eight-tenths of an inch in five minutes. Something more than the maximum observed rate is desirable, and it would seem, therefore, that one inch in five minutes would be amply sufficient. I would suggest that this figure, or its equivalent, two-tenths of an inch in one minute, be adopted, instead of the range of precipitation which Mr. Skinner has suggested.

I agree with Mr. Thomas that frequency will, in all probability, have a considerable effect on the flash-over voltage of the insulator; if this is shown to be the case, the insulator should be tested at the frequency for which it is designed. The flash-over voltage will also probably depend a good deal upon the method of voltage control in making the test. The discordant results obtained with different testing equipments are, no doubt, due in part to the fact that the voltage is usually controlled by means of a rheostat in series with the testing transformer. This method of control will, under some conditions, materially modify the wave-form. If the voltage be varied by varying the field of the generator, there is a much better chance for concordant results.

**Clayton H. Sharp:** In reference to the production of a proper spray or precipitation for use in the testing of insulators, I am having constructed at present an apparatus which has been suggested by an arrangement in use, I believe, in the German Reichsanstalt. This arrangement consists of a large cylindrical vessel, which has a considerable number of little tubes running out from the bottom of it, equally spaced in centers of one and one-half inch squares. The top is closed and has a micrometer valve by which the admission of air can be controlled. On the side there is an ordinary gauge glass to show the level of the water and the rate of precipitation. These tubes will have cotton wicking stuffed into them of proper thickness, and a tail of fine wire, to enable the drops to fall off. With an arrangement of that kind, I hope to get a uniform dropping of the water; in other words, an imitation of a rainstorm, which can be regulated by changing the admission of air by the valve, and in which the rate of precipitation can be measured on the gauge glass at the side. By setting up a fan at one side the effect of a hard wind may be obtained. I do not know that such an apparatus has ever been used, at any rate in this country; if it has I would like to know what the results of experience with a device of that kind have been. It seems to me that such a device has a great advantage, coming nearer to an actual rainstorm than any ordinary spraying arrangement. It gives separate drops of water, and that is what we want.

**E. M. Hewlett:** Regarding the rain test on insulators, some folks like heavy rain, some like a flood, and some are satisfied with a mist. I do not believe you can satisfy everybody. It looks as though possibly a steam test might give a better average condition; there will not be so many conditions to balance up. You can get quite a film of moisture on the surface with the steam test, and can duplicate it more readily than the rain test, making better average tests. The rain test is of value in determining insulator design.

**Chas. P. Steinmetz:** There is one test which I do not find mentioned in Mr. Skinner's paper, and that is the test of the insulator after being submerged in water for a considerable period, a week or ten days, or more. A porcelain insulator may well stand all the tests outlined here, and may fail in service after a few weeks or months, by absorption of moisture through hair cracks in the glaze, due to incomplete vitrification or to porosity of the material. Porcelain is by no means an ideal material for an insulator. It is a heterogeneous mass, more or less completely vitrified in its interior, and covered with a glaze. If the vitrification is perfect, it is just as good and uniform as glass, but if the vitrification is not perfect, as long as the glaze keeps the moisture out it will stand, but as soon as by temperature variation of the air the glaze begins to acquire hair cracks, moisture soaks in and the insulation strength goes down. Glass would be preferable except that it is mechanically weak, and is hydroscopic, and so covers itself with a film of moisture. I am not entirely satisfied with such a test as immersion in water, but I bring it to your attention. Perhaps some one else might suggest a better way of testing a small percentage of insulators for absorption of moisture and decrease of disruptive strength resulting therefrom by long-continued exposure to water and atmospheric conditions.

I also raise the question whether it is advisable, as proposed in the paper, to allow any tests of less than twice the rated voltage. Here tests are proposed of one and one-quarter and one and one-half times the rated voltage. Now, you know that in our standardization rules, no voltage test is permitted on any apparatus of less than twice the rated voltage. That is the minimum test permitted. Here we have recommended tests under undesirable, but still actually existing conditions, of one and one-quarter times the rated voltage. The margin is rather small, probably too small. Many of us feel that at the present time the insulator is the weakest link in the long-distance transmission system. The occasional use, for instance, of 60,000-volt insulators on 40,000-volt systems also shows that the engineers feel that the extra high-voltage insulator is really not quite as good, does not have the same margin of safety, as other apparatus. It would be much more consistent if we insisted in testing the insulators to ascertain that they have the same margin of disruptive strength as all other apparatus is supposed to have, instead of so moderating the tests as to allow the insulators to be rated at a voltage to which they are not entitled on the basis of the margin of safety standard for all other parts of the system.

In regard to specifying the number of insulators tested on one trial, etc., my understanding is that the paper proposed additional matter to the rules of our Standardization Committee, so in this connection our standardization rules—which specify how many insulators you can test from one transformer, that is, how large the capacity current can be compared to the tranformer capacity—would apply. All those features that are specified by our standardization rules are implied, and the paper merely brings forward additional matter.

**C. E. Skinner:** I am a little surprised that nothing has been said in the discussion in regard to the dew test. I do not know whether this test has been used to any great extent or not, but those who have used it claim that it is far more satisfactory than any rain test, and also more severe, and it is one that ought to be relatively easy to repeat.

In regard to the number of insulators which may be tested on a given size transformer, I would say that Dr. Steinmetz has already covered the point. You will note that the paragraphs on voltage control, capacity of testing transformers, etc., are practically copied from the standardization rules. They are partly repeated here, in order to make the specification complete.

In regard to the question of placing the insulator vertically, and having an angular spray, I agree entirely with Mr. Mershon; no method has yet been brought to my attention which could be controlled with sufficient accuracy to allow repetition. This specification is intended to be a performance specification, and to have a performance specification you must be able to repeat your tests. The best we have been able to do in our laboratory in making tests is to get a spray which, measured by the rain gauge, taking successive squares in the spray, showed a variation of very approximately that given in the specification, that is, 0.2 to 0.3 inches per minute. I do not believe it makes very much difference whether it is a little more or a little less. I think that with that amount of water the results will be about the same. Mr. Mershon referred to a rate of one inch in five minutes—which is equivalent to 0.2 inch per minute. In all the communications that I received, I did not hear of the method mentioned by Dr. Sharp, although I was in communication with some of the German porcelain manufacturers. As a matter of fact, their letters did not give me very much information in regard to their method of obtaining the spray. I think that it would be impossible to use a fan and blow the spray the same on two successive days—that it would be out of the question to repeat tests of that kind.

The steam test suggested by Mr. Hewlett I think is virtually covered by what I called the dew test here. It is merely gotten at in a little different way, and in a way which is frequently met in practice; that is, the insulator is cooled down during the night, and in the morning, particularly in the tropics, and in places where the temperature rises suddenly, the insulator becomes completely coated over its entire surface with a layer of moisture.

The immersion test suggested by Dr. Steinmetz I think would be a very good one to add to the performance test, but I think it would be rather burdensome to make on all insulators.

In regard to the over-potential test of one and a quarter and one and a half times, I would refer to the introduction of the paper, in which I disclaim any great responsibility for the data there given; my own idea is that the tests specified are rather too low. I would like to see them higher, and if insulators can be purchased at a reasonable price for use on transmission lines under the more severe conditions, I would like to see the double-potential test substituted for the one given.

**Ralph D. Mershon:** As regards the dew test, both as suggested by Mr. Skinner and by Mr. Hewlett, it does not seem a definite test. Moist atmosphere—what does that mean? It would make a great deal of difference in the condition of the insulator just how long it is left out, and just what that moist atmosphere means—how can you give any definite condition?

**C. E. Skinner:** I have not made the dew test myself. It was proposed by two or three other persons who claimed they had made this test and found it perfectly satisfactory. If the air contains a fair amount of moisture, there will be a sufficient collection of moisture on the surface of the insulator to make it flash over, *under the test specified.*

**E. M. Hewlett:** We have made the steam test, and find it is easier to make the steam test than it is to get up in the morning early so as to find the insulator cool enough to test it with the dew test. We put the steam on the insulator with a hose until the surface is covered with condensed steam, and then make the voltage test.

**N. J. Neall** (by letter): Routine test. Inspection. I doubt very much the wisdom of allowing so large a variation as ± 5 per cent. in general over-all dimensions from the designed size. This is particularly critical for extra high-potential designs, where an insulator 14 inches in diameter and 14 inches high may have a considerably lower arcing test than one 15 inches in diameter by 15 inches high. I think ± 2.5 per cent. would be safer.

Dielectric tests. This is a good commercial rule for testing parts, but due consideration should be given the potential gradient of the insulator as a whole as well as the individual electrostatic capacities of the parts in series therein. Actually I would expect the top of an insulator to get almost line potential strain, particularly if the pin be grounded. I would call for three times the usual line voltage, 2.5 times is not high enough. There is no designation as to what constitutes a " lot." I should suggest a selective test from each kiln fired.

Design test. This permission to test as many as 5 per cent. is generous indeed. In general, a much smaller percentage than this should suffice.

Rain tests. 1.5 times normal voltage is too low; it should be at least 2 times. Likewise for dew test,—of shorter duration than 5 minutes, say 1 or 2 minutes. In none of these specifications is the important requirement, " with pin grounded," mentioned.

Methods of making tests. Rain test. The proposed angular position of the insulator with respect to a vertical rain does not appeal to me, because the whole combination of static field and reflected rain as found in service is apparently inadequately reproduced in this way. I prefer the rain at an angle instead. This detail requires further working out.

In addition to the preceding details, I wish to add the following: For testing insulators local conductors should be of large diameter to cut down the excessive ionization usually present in such tests. There should be some " table " of the number of insulators of given size that it is permissible to simultaneously test with a testing transformer of given capacity. In testing large insulators in large numbers for extra high voltage, the charging current alone may impair the value of the test. There must be some recognized method of measuring the voltage. Just as soon as the true character of spark-gaps is known it should be applied to this work authoritatively. In the meanwhile I would suggest the use of shielded spark-gaps with spherical tips—needles being more liable to error and burdensome in practice. For general testing, the voltage by ratio is desirable, provided it can be kept free of error; and the specification as to appropriate size of apparatus might include among its requirements a description of the apparatus.

I have already called attention, in my recent paper on lightning before the Institute, to the desirability of equivalent spark-gap measurements of insulators as indications of their non-arcing power. The arcing-over test of the insulator is no more indicative of its efficiency than the same test on a lightning arrester.

The tendency of the proposed specification seems to be a letting down rather than a stiffening of those requirements heretofore generally followed. I think the record of operation of high-tension transmission systems will show the wisdom of making this element thereof stronger than is proposed in these specifications.

Aside from these criticisms of details, I wish to state my belief that such a specification as here proposed by Mr. Skinner is highly desirable.

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# VOLTAGE RATIO IN SYNCHRONOUS CONVERTERS WITH SPECIAL REFERENCE TO THE SPLIT-POLE CONVERTER

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BY COMFORT A. ADAMS

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*Introduction.* The interesting discussion on the split-pole converter at the February New York meeting of the Institute instigated the following paper, which consists of a purely theoretical analysis, the principal object of which is to show how the field distortion of a split-pole converter does not necessarily involve electromotive force distortion.

Incidentally there will be developed a method of analysis by which the direct electromotive force or any one of the alternating electromotive forces is determined analytically from the harmonic analysis of the flux distribution curve, thus establishing a simple and direct connection between the shape of the flux distribution curve, and the shapes as well as the magnitudes of the resulting electromotive forces.

## DEFINITIONS

*Brush electromotive force and tap electromotive force.* The electromotive force between two adjacent commutator brushes will be called the *brush electromotive force* and that between collector rings the *tap electromotive force*.

*Belt.* In the ordinary closed-coil, two-layer lap winding, a series path between two adjacent brushes or between two adjacent taps, is made up of a set of coils, half of the sides of which, in the tops of slots, form a *belt* of conductors; the other half, in the bottoms of other slots, form a similar *belt*, but connected in the opposite direction. In the wave winding a series path contains as many such sets of coils or pairs of *belts* as there are pairs of poles. With a full pitch winding the two belts of any pair are 180 electrical degrees apart between centers; but less in a fractional pitch winding.

For a series path between brushes the span of each belt is 180 electrical degrees, and for a path between taps the belt span depends upon the number of phases; 180° for the single-phase or diametral connection, 120° for the three-phase, 90° for the quarter-phase, etc. In Fig. 1 is shown the location of a pair of belts forming a path between brushes, for three different values of the coil pitch. The solid lines indicate the top slot belts and the broken lines bottom slot belts. The brushes are also shown, together with the flux distribution curve. The broken curve shows a split-pole distortion..

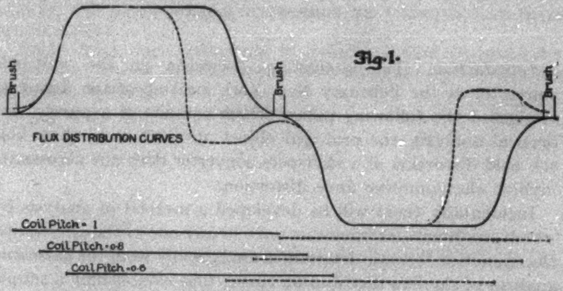


Fig. 1.

*Differential-factor*. The brush-belts are as a whole stationary, although the individual components thereof are cutting through the flux, each belt remaining under a particular pole so that all of its elements are cutting flux in the same direction; but a tap-belt revolves as a whole and at times lies across parts of two poles, thus generating opposing electromotive forces in the two parts of the belt and reducing the effectiveness of electromotive force generation by introducing what may be called *differential-action.* The average electromotive force induced in this belt is therefore less than that induced in an equal number of active conductors in a brush-belt, and the factor by which it is less will be called the *differential-factor,* since it takes account of the differential cutting of the flux.

A differential action also takes place in the brush-belts, in the case of fractional-pitch windings, or when the brushes are displaced from the neutral points.

*Form-factor.* The tap voltage differs from the brush voltage induced in the same number of conductors, not only because of the differential action which reduces the average useful electromotive force, but also because the effective or root-mean-square tap voltage differs from the average by a factor called the *form-factor* which depends upon the wave-shape.

If $E$ and $E_1$ be the brush and the single phase (or diametral) tap electromotive force, respectively, we may write

$$E_1 = k_d \, k_f \, E \tag{1}$$

where $k_d$ and $k_f$ are the differential- and the form-factor respectively. These two constants are closely connected and are commonly combined into a single constant, but they represent two distinct phenomena which are not inter-dependent, since they may be combined in a great variety of proportions. For example, in the split-pole converter it is possible so to proportion the parts as to change the differential-factor, and therefore the voltage ratio over a wide range without producing much change in the form-factor or the wave-shape.

The writer's present purpose is to show how this can be done.

## FLUX DISTRIBUTION CURVE AND SINGLE-CONDUCTOR ELECTROMOTIVE FORCE

Imagine a single conductor to cut through the gap flux at normal speed; the induced electromotive force will be at each instant proportional to the density of flux through which it is cutting, and the resulting electromotive force curve will have the same shape as the *flux distribution curve.* It will be convenient to deal with this elementary electromotive force curve in considering the resultant electromotive force of a whole belt. The elementary electromotive force curve may be expressed algebraically in the form of Fourier's series, thus;

$$\left.\begin{array}{l} e' = a_1 \sin \omega t + a_3 \sin 3\omega t + a_5 \sin 5\omega t + a_7 \sin 7\omega t + \quad \text{etc.} \\ + b_1 \cos \omega t + b_3 \cos 3\omega t + b_5 \cos 5\omega t + b_7 \cos 7\omega t + \quad \text{etc.} \end{array}\right\} \tag{2}$$

where $\omega = 2 \pi n$, and $n$ is the fundamental frequency.

For our present purpose equation (2) may be more conveniently written:

$$e' = a_1 \left| \begin{array}{l} \sin \omega t + q_{a_3} \sin 3\omega t + q_{a_5} \sin 5\omega t + \quad . \quad . \quad . \quad . \quad . \quad . \\ \qquad + q_{am} \sin m\,\omega t + \text{etc.} \\ q_{b_1} \cos \omega t + q_{b_3} \cos 3\,\omega t + q_{b_5} \cos 5\,\omega t \; + \quad . \quad . \quad . \quad . \\ \qquad + q_{bm} \cos m\,\omega t + \text{etc.} \end{array} \right| \tag{3}$$

$$\text{where } q_{am} = \frac{a_m}{a_1} \text{ and } q_{bm} = \frac{b_m}{a_1}$$

## Relation of Brush Voltage to the Elementary or Single-Conductor Electromotive Force

It will be assumed in what follows that the harmonic analysis of the single-conductor electromotive force was so carried out that the zero of time in equation (3) corresponds to the instant when the conductor in question is passing under one of the brushes.

With this assumption, the brush voltage, which is proportional to the area or to the average value of the elementary electromotive force wave between brushes, is:

$$E_{dc} = N \frac{2}{\pi} a_1 \left[ 1 + \frac{1}{3} q_{a_3} + \frac{1}{5} q_{a_5} + \frac{1}{7} q_{a_7} + \frac{1}{9} q_{a_9} + \text{etc.} \right] \tag{4}$$

or if we designate $\frac{2}{\pi} N a_1$ by $E_1$

$$E_{dc} = E_1 \left[ 1 + \frac{1}{3} q_{a_3} + \frac{1}{5} q_{a_5} + \frac{1}{7} q_{a_7} + . \;\; . \text{ etc.} \right] \tag{4a}$$

where $N$ is the number of conductors in series between brushes.

The cosine terms drop out, since the average value of the cosine over a half cycle beginning with zero, $\pi$, or any multiple thereof, is zero. The average value of an odd $m$th harmonic sine term taken over a half-cycle of the fundamental is $1/m$th of the average value of a half cycle of that term, since the other $m$-1 half-waves cancel out.

## Relation of Tap Voltage to the Elementary or Single-Conductor Electromotive Force

For this purpose write equation (3) as follows:

$$\begin{aligned} e' = a_1 [ & q_1 \sin (\omega t + \theta_1) + q_3 \sin (3\,\omega t + \theta_3) \\ & + q_5 \sin (5\,\omega t + \theta_5) + \quad . \quad . \quad . \quad q_m \sin (m\,\omega t + \theta_m) + \text{etc.} ] \end{aligned} \tag{5}$$

where $q_m = \sqrt{q^2_{am} + q^2_{bm}}$, and $\theta_m = \tan^{-1} \frac{b_m}{a_m}$ is measured in $m$th harmonic radians.

A little consideration will show that $q_1$ $(= \sqrt{1+q_{b_1}^2})$ does not differ much from unity except in cases of considerable distortion, and that it is equal to unity in the ordinary converter where the flux distribution curve is symmetrical about the center of the pole face, or with the three-part split-pole and symmetrical distortion. A displacement of the brushes would have the effect of increasing $q_1$.

The electromotive force of a single slot will have the same shape as $e'$ and will differ only in magnitude according to the number of conductors per slot. The electromotive force of a given alternating-current belt may be considered as made up of as many components as there are slots per belt, each component being the electromotive force of a single slot and differing in phase from that of an adjacent slot by the electrical angular pitch of the slots.

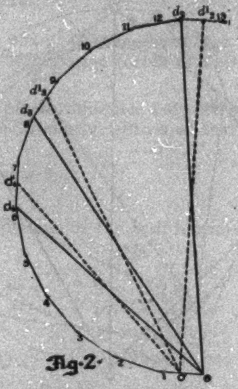
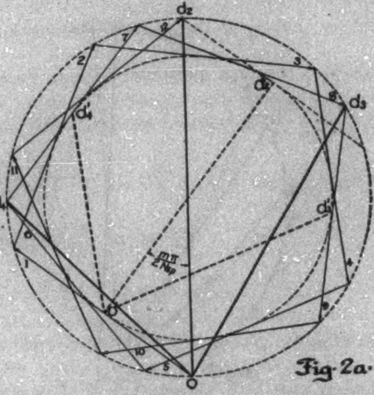


Fig. 2.

Then the electromotive force of the belt will have for its fundamental the vector sum of the fundamentals of the electromotive forces of the several slots of that belt, and for its $m$th harmonic the vector sum of the $m$th harmonics of the slots of that belt; but the phase difference between the latter will be (in harmonic degrees) $m$ times as great as that of the fundamentals. For example, Fig. 2 shows the fundamental slot electromotive forces extending over 180 electrical degrees of armature circumference, for a converter with 12 slots per pole, while Fig. 2a shows the corresponding twelve fifth harmonic slot electromotive forces. In both Figs. the electromotive forces are numbered in the order of their respective slots starting at the point $o$. In Fig. 2, $\overline{o\,d_2}$ is the diametral or 180° fundamental electromotive force, $\overline{o\,d_3}$ the delta or 120° electromotive force and $\overline{o\,d_4}$ the quarter phase or 90° electromotive force. Similarly in Fig. 2a, $\overline{o\,d_2}$ is the vector sum of the twelve fifth-harmonic slot electromotive forces, that is, the 180° fifth harmonic; $\overline{o\,d_3}$ the vector sum of the fifth harmonic electromotive forces of slots numbers one to eight inclusive, that is, the 120° fifth harmonic; and $\overline{o\,d_4}$ the 90° fifth harmonic. A little considera-



Fig·2a·

tion will show that the ratio of the resultant to the arithmetical sum of the fifth harmonic slot electromotive forces is small as compared with the ratio of the resultant to the arithmetical sum of the fundamental slot electromotive forces. These ratios are the differential-factors for the fifth harmonic and the fundamental respectively, and will be labelled $k_{d_5}$ and $k_{d_1}$. The quantity

$$k_{r_5} = \frac{k_{d_5}}{k_{d_1}}$$

will be called the fifth harmonic *reduction-factor*, and is the ratio in which the fifth harmonic of the belt electromotive force is reduced from that of the slot electromotive force (or the flux distribution curve); that is, if the amplitude of the fifth harmonic of the slot electromotive force is $q$ per cent. of the fundamental, the amplitude of the fifth harmonic of the belt electromotive force will be $k_{r_5} \times q$ per cent. of its fundamental.

These relations may be generalized as follows:

Let $N_{sp}$ = slots per pole.

and $p'$ = the number of belt spans per electrical circumference, ($p' = 2$ for diametral connection, and 3 for 3 phase delta or 6 phase double delta).

Then $\frac{\pi}{N_{sp}}$ = the phase difference between the fundamental electromotive forces of two adjacent slots.

$\frac{m\pi}{N_{sp}}$ = the phase difference between the $m$th harmonic electromotive forces of two adjacent slots.

and $\frac{2N_{sp}}{p'}$ = slots per belt.

The total phase rotation of the $m$th harmonic in all the slots of the belt will be

$$\frac{m\pi}{N_{sp}} \times \frac{2N_{sp}}{p'} = \frac{2m\pi}{p'}$$

and if the diagram (such as Fig. 2a) be reduced to unit radius the resultant of the $\frac{2N_{sp}}{p'}$ $m^{\text{th}}$ harmonics will be $2 \sin \frac{m\pi}{p'}$.

On the same basis the $m^{\text{th}}$ harmonic of the slot electromotive force is $2 \sin \frac{m\pi}{2N_{sp}}$ and the arithmetical sum of the $\frac{2N_{sp}}{p'}$ $m^{\text{th}}$ harmonics is $\frac{2N_{sp}}{p'} \times 2 \sin \frac{m\pi}{2N_{sp}}$

Thus the differential factor for the $m$th harmonic of the belt electromotive force is

$$k_{dm} = \frac{p'}{2N_{sp}} \frac{\sin \frac{m\pi}{p'}}{\sin \frac{m\pi}{2N_{sp}}} \tag{6}$$

and that for the fundamental

$$k_{d_1} = \frac{p'}{2\,N_{sp}} \; \frac{\sin \dfrac{\pi}{p'}}{\sin \dfrac{\pi}{2\,N_{sp}}} \tag{7}$$

The reduction-factor for the $m$th harmonic is then

$$k_{rm} = \frac{k_{dm}}{k_{d_1}} = \frac{\sin \dfrac{m\,\pi}{p'}}{\sin \dfrac{\pi}{p'}} \; \frac{\sin \dfrac{\pi}{2\;N_{Sp}}}{\sin \dfrac{m\,\pi}{2\;N_{Sp}}} \tag{8}$$

The first factor of the expression for $k_{rm}$ is independent of the number of slots, and its numerical value for various phases and harmonics is shown in Table I.

Table I giving values of $\sin \dfrac{m\,\pi}{p'} \div \sin \dfrac{\pi}{p'}$

TABLE I.

| $m =$ | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| $p' = 2$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $p' = 3$ | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| $p' = 4$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $p' = 6$ | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 |

The second factor of the formula for $k_{rm}$ is independent of $p'$, and its numerical values for various values of $N_{sp}$ and $m$, are shown in Table II.

Table II giving values of $\sin \dfrac{\pi}{2\,N_{Sp}} \div \sin \dfrac{m\,\pi}{2\,N_{Sp}}$.

TABLE II.

| $N_{sp} =$ | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | $\infty$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $m =$ 3 | 0.351 | 0.344 | 0.340 | 0.338 | 0.3368 | 0.3362 | 0.3358 | 0.3355 | 0.3353 | 0.3351 | $\frac{1}{3}$ |
| $m =$ 5 | 0.235 | 0.222 | 0.214 | 0.2101 | 0.2081 | 0.2062 | 0.2051 | 0.2042 | 0.2034 | 0.2029 | $\frac{1}{5}$ |
| $m =$ 7 | 0.199 | 0.1755 | 0.1646 | 0.158 | 0.154 | 0.152 | 0.150 | 0.149 | 0.1477 | 0.1467 | $\frac{1}{7}$ |
| $m =$ 9 | 0.198 | 0.158 | 0.141 | 0.132 | 0.126 | 0.123 | 0.1208 | 0.119 | 0.1177 | 0.1166 | $\frac{1}{9}$ |
| $m =$ 11 | 0.2345 | 0.1583 | 0.1316 | 0.1185 | 0.1111 | 0.106 | 0.103 | 0.1009 | 0.0992 | 0.0979 | $\frac{1}{11}$ |
| $m =$ 13 | 0.351 | 0.1755 | 0.1317 | 0.1124 | 0.102 | 0.961 | 0.0920 | 0.08916 | 0.08702 | 0.08533 | $\frac{1}{13}$ |
| $m =$ 15 | 0.995 | 0.2214 | 0.1413 | 0.1126 | 0.0986 | 0.0903 | 0.08492 | 0.0813 | 0.07865 | 0.07665 | $\frac{1}{15}$ |
| $m =$ 17 | 1.000 | 0.3444 | 0.1644 | 0.1185 | 0.0985 | 0.0875 | 0.0807 | 0.0761 | 0.0720 | 0.0706 | $\frac{1}{17}$ |
| $m =$ 19 | 0.351 | 1.000 | 0.214 | 0.132 | 0.100 | 0.0875 | 0.0788 | 0.073 | 0.069 | 0.0662 | $\frac{1}{19}$ |

Except for the 3 and 6 phase, third, ninth and fifteenth harmonics, the values in Table II are those of $k_{r_m}$, the reduction-factor, or the ratio of the per cent. harmonic in the tap electromotive force to the per cent. harmonic in the flux distribution curve.

An inspection of Tables I and II shows that for the single-phase or diametral connection and for a very large number of slots per pole, the reduction-factor is one-third for the third harmonic, one-fifth for the fifth harmonic, one-seventh for the seventh harmonic, etc; and that for a moderate number of slots per pole, the only change is a slight increase in the reduction-factor, this increase being greater for the higher harmonics.

Table I shows that for the delta or 120° connection ($p' = 3$), the third, ninth and all other harmonics which are multiples of three, drop out. This may be explained in several ways: first, a third or ninth harmonic would mean a circulating electromotive force around the closed-coil winding, which is impossible if the north and south pole fluxes are similarly distributed, since under this last assumption the electromotive forces of the two halves of the winding must be equal and opposite at each instant; secondly, the differential-factor of the third, ninth or fifteenth harmonic is zero for the 120° connection, since its phase rotation which is 3, 9 or 15 times that of the fundamental (120°), is a multiple of 360°. In other respects than in the disappearance of these harmonics the reduction factor is the same for the 120° as for the 180° connection.

For the quarter phase, or 90° connection, the reduction-factor is exactly the same as for the 180° connection; and for the 60° connection the only difference is that the third, ninth and fifteenth harmonic reduction-factors are doubled instead of being eliminated as in the 120° connection; that is, the reduction-factor for the third harmonic is two-thirds for the 60° connection, in place of one-third for the 180° connection and zero for the 120° connection. The explanation of this is, that with a fundamental phase rotation of 60°, the third harmonic phase rotation is 180°, giving a diameter as resultant, which is relatively twice as great as the 60° chord of the fundamental resultant. The ninth, fifteenth, etc., harmonics would add multiples of 360° to the phase rotation, leaving the resultant a diameter as in the case of the third harmonic.

*Fractional-pitch or short-chord windings.* Thus far the electromotive force of only a single belt has been considered. If the winding has the full pitch of 180°, the electromotive forces of the two belts of any pair will be in exact phase, and their resultant will have the same shape as the electromotive force of a single belt. But if a *fractional-pitch* or *short-chord* winding be employed, the two belt-electromotive forces will differ in phase by an amount depending upon the pitch deficiency, and their resultant may not have the same shape; in general it will not, unless the two component belt electromotive forces are sinusoidal.

Let $\lambda_c$ designate the coil pitch in terms of full pitch. Then $1-\lambda_c$ is the pitch deficiency, and $(1-\lambda_c)\pi$ is the phase difference between the fundamental electromotive forces of the two belts; see Fig. 3, where $O\,A$ and $A\,B$ are the two equal fundamental electromotive forces and $OB$ their resultant. The differential or pitch reduction-factor for the fundamental electromotive force is

$$\overline{OB} \div (\overline{OA} + \overline{AB}) = \sin \frac{\pi}{2}\, \lambda_c$$

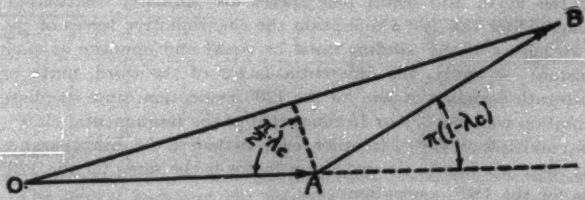


FIG. 3

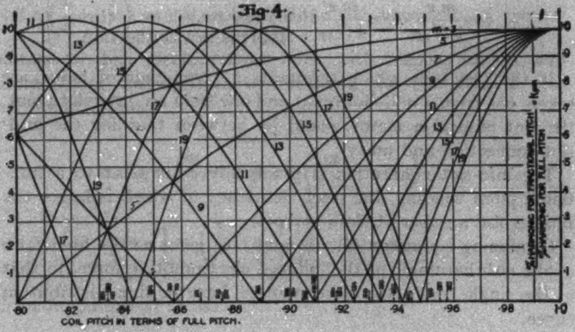
and that for the $m$th harmonic is $\sin \frac{m\,\pi}{2}\, \lambda_c$. The ratio of the latter to the former will be designated the $m$th harmonic pitch factor, it is

$$k_{pm} = \frac{\sin m \frac{\pi}{2}\, \lambda_c}{\sin \frac{\pi}{2} \lambda_c} = \frac{\text{per cent. of } m\text{th harmonic in fractional pitch winding}}{\text{per cent. of } m\text{th harmonic in full pitch winding}} \qquad (9)$$

This is plotted in Fig. 4 for the odd harmonics up to the nineteenth and for values of the coil pitch from 0.8 to 1.0. From the curves of Fig. 4, it appears that it would be possible to practically wipe out any one of the higher harmonics by a proper choice of pitch, although the reduction necessary to eliminate, say the fifth harmonic, would probably cause serious commutation difficulties. It is interesting to note in this connection that a pitch of 0.833 (10 slots in 12, 15 in 18, 20 in 24) would reduce the fifth, seventh, seventeenth and nineteenth harmonics to about one-quarter of their full pitch values. This would leave for the delta or double delta connections only the eleventh and thirteenth harmonics, since the third, ninth, fifteenth, and twenty-first harmonics are entirely absent in this case.

*Fractional slot connection.* Thus far it has been assumed that each phase belt comprised a whole number of slots; but it is obvious that this is not at all necessary, for even when the number of slots per pair of poles is a multiple of the number of phases, the taps may be taken off at junctions in the centers of slots. In this case there would be two half-slot electromotive force vectors at the ends of the whole slot vectors. This is shown in Fig. 2 where $\overline{o' d_2'}$, drawn from the middle of slot electromotive force number one to the middle of slot electromotive force number thirteen, is the 180° fundamental resultant, and in Fig. 2a where $\overline{o' d_2'}$ is in the same way the 180° fifth harmonic resultant. Similarly $\overline{o' d_3'}$ and $\overline{o' d_4'}$ are the corresponding resultants for the 120° and 90° electromotive forces.

Fig. 4.



An inspection of Fig. 2a will show that this mid-slot connection has reduced the resultant harmonic by the factor, $\cos \frac{m \pi}{2 N_{sp}}$ which approaches zero as $m$ and $N_{sp}$ approach equality. Thus if $N_{sp}$ is large, some of the higher harmonics are practically wiped out by this mid-slot connection, and if $N_{sp}$ is small all of the lower harmonics are reduced and some intermediate ones almost eliminated.

For other fractional slot connections the reduction is less. Designate the fractional slot reduction-factor by $k_{sm}$ and it is:

$$k_{sm} = \left\{ \begin{array}{l} \cos\dfrac{m\pi}{2N_{sp}} \text{ (for half-slot connection).} \\ \\ \cos\dfrac{m\pi}{2N_{sp}} \div \cos\dfrac{m\pi}{6N_{sp}} \text{ (for a one-third or a two-thirds slot connection} \\ \\ \cos\dfrac{m\pi}{2N_{sp}} \div \cos\dfrac{m\pi}{4N_{sp}} \text{ (for a one-fourth or a three-fourths slot connection.} \end{array} \right\} \quad (10)$$

If the two taps which terminate a given pair of belts, are taken, one from a mid-slot point and one from an interslot point, the slot reduction factor would lie between that for the mid-slot connection and unity.

The mid-slot connection is practically equivalent to a fractional pitch winding, the pitch deficiency of which is larger the smaller the number of slots per pole.

Combining equations (8), (9) and (10) gives as the final ratio of the $m$th harmonic of the induced electromotive force, to that of the single conductor electromotive force or flux distribution curve,

$$k_m = k_{rm} \times k_{pm} \times k_{sm} = \frac{\sin \dfrac{m\pi}{2}\lambda_c}{\sin \dfrac{\pi}{2}\lambda_c} \times \frac{\sin \dfrac{m\pi}{p'}}{\sin \dfrac{\pi}{p'}} \times \frac{\sin \dfrac{\pi}{2N_{sp}}}{\sin \dfrac{m\pi}{2N_{sp}}} \times k_{sm} \quad (11)$$

Equation (10) includes the effects of all the thus-far-considered factors upon the *magnitudes* of the harmonics.

Consider now the phases of the harmonics.

*Phases of harmonics.* Referring to Figs. 2 and 2a, the total phase rotation of the fundamental is $\dfrac{2\pi}{p'}$. Thus the phase of the fundamental of the resultant or belt electromotive force with respect to the fundamental of the electromotive force of slot

No. 1 is, in fundamental radians

$$\alpha_1 = \frac{\pi}{p'} - \frac{\pi}{2\,N_{sp}} = \pi\left(\frac{1}{p'} - \frac{1}{2\,N_{sp}}\right)$$

The total phase rotation of the $m$th harmonic is $\frac{2\,m\,\pi}{p'}$

Let $w$ = nearest whole number less than $\frac{m}{p'}$ and

$w_s$ = " " " " " $\frac{m}{2\,N_{sp}}$

Then the equivalent phase rotation of the $m$th harmonic is $2\,\pi\left(\frac{m}{p'} - w\right)$ and the phase of the $m$th harmonic of the resultant or belt electromotive force with respect to the $m$th harmonic of the electromotive force of slot No. 1 is, in $m$th harmonic radians

$$\alpha_m = \pi\left(\frac{m}{p'} - w\right) - \pi\left(\frac{m}{2\,N_{sp}} - w_s\right)$$

$$= \pi\left[m\left(\frac{1}{p'} - \frac{1}{2\,N_{sp}}\right) - (w - w_s)\right]$$

or in fundamental radians

$$\alpha_m' = \pi\left[\left(\frac{1}{p'} - \frac{1}{2\,N_{sp}}\right) - \left(\frac{w - w_s}{m}\right)\right]$$

Thus in passing from the slot electromotive force to the resultant or belt electromotive force, the relative phase of the $m$th harmonic with respect to the fundamental is changed by an amount which is, in fundamental radians

$$\beta_m' = \alpha_m' - \alpha_1 = -\frac{\pi}{m}\,(w - w_s) \qquad (12)$$

or, in $m$th harmonic radians,

$$\beta_m = m\,(\alpha_m' - \alpha_1) = -\pi\,(w - w_s) \qquad (13)$$

But $w$ and $w_s$ are whole numbers and $\beta_m$ is therefore always a multiple of $\pi$. Moreover $w_s$ is practically always zero, since when

$$m = 2 N_{sp}$$

the harmonic is so small as to be wholly negligible. With this assumption, $\beta_m$ is zero when $w$ is even, and $\pi$ when $w$ is odd. That is, when $w$ is odd the $m$th harmonic of the belt electromotive force is reversed in phase as compared with the same harmonic in the slot electromotive force.

For example, consider a slot electromotive force which consists of a fundamental and a prominent third harmonic; follow this harmonic into the various belt electromotive forces.

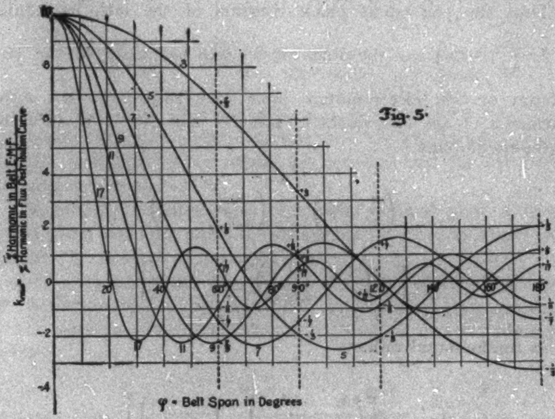


Fig. 5.

For the single phase or diametral connection, $p' = 2$ and $w = 1$. Thus the third harmonic is *inverted* as well as being reduced to one-third of the percentage value which it had in the slot electromotive force. That is, if the slot electromotive force be flat topped, the 180° electromotive force will be peaked and vice versa, but less so than the slot electromotive force.

For the three-phase or delta connection, $p' = 3$ and $w = 1$; but the amplitude of the third harmonic in the 120° electromotive force is zero.

For the quarter-phase or 90° connection, $p' = 4$ and $w = 0$; therefore the third harmonic is not reversed, but is merely reduced to one-third of its slot percentage. That is, if the slot electromotive force be peaked, the 90° electromotive force will be peaked but less so; and if the slot electromotive force be flat topped, the 90° electromotive force will be flat topped but less so.

For the six-phase connection, $p' = 6$ and $w = 0$. The third harmonic is not reversed and is reduced to two-thirds of its slot percentage.

Follow this third harmonic from the six-phase back through the four, three, and two (single) phase. It is relatively large (two-thirds) and positive in the six-phase, reduced to one-third in the quarter-phase, vanishes in the three-phase, and reappears inverted in the single-phase with a relative value of one-third.

Follow the fifth harmonic in the same way. In the 60° belt it is positive and of one-fifth magnitude; in the 72° belt zero; in the 90° belt inverted and of one-fifth magnitude; the same in the 120° belt, having passed through a maximum between these last two points; and one-fifth positive again in the 180° belt. It thus appears that the change of belt span alters the magnitude but not the phases of the harmonics. This is just what was to be expected, since the phase of any given harmonic with respect to the fundamental is the same in each of the elementary e.m.fs. of which the tap e.m.f. is composed, and must therefore be the same in the resultant or tap e.m.f.

In order to see this relation more clearly, start with the flux distribution curve or the single-conductor electromotive force, assume an infinite number of slots and imagine the belt span to be increased gradually. The per cent. magnitude of any harmonic will gradually decrease through zero to a negative maximum, then back again to a positive maximum, etc., without any change of phase other than that involved in reversal. If the angle of belt span be designated by $\phi$, the reduction factor for this case of an infinite number of slots will be

$$k_{rm}\infty = \frac{1}{m}\sin\frac{m\,\phi}{2} \div \sin\frac{\phi}{2} \qquad (14)$$

Values of $k_{rm}\infty$ for several harmonics and for all values of belt span up to 180° are shown plotted in Fig. 5. These curves are instructive as showing clearly the general relation between belt span and the relative magnitudes of the several harmonics, although they do not take account of the number of slots per pole.

Negative values of $k_{rm}\infty$ indicate that the harmonic is inverted.

### TAP VOLTAGE.

Adopting the notation of equation (5) the $m$th harmonic of any tap electromotive force may be completely expressed thus:

$$k_m q_m \sin (m \omega t + \theta_m + \pi w),$$

where $w$ is as already defined, and $k_m$ is given by equation (11).

The amplitude of the fundamental of the tap voltage is

$$a_{t_1} = k_{d_1} \frac{2N}{p'} q_1 a_1$$

where $N$ is the number of conductors in series between brushes, $\frac{2N}{p'}$ the number of conductors in series between taps, $q_1 a_1$ the amplitude of the fundamental of the single conductor electromotive force and $k_{d_1}$ the fundamental differential-factor, which, for all practical purposes, may be taken as equal to $\frac{p'}{\pi} \times \sin \frac{\pi}{p'}$, the limiting value of equation (7) as $N_{sp}$ approaches infinity. The amplitude of the tap voltage fundamental is then

$$a_{t_1} = \frac{2}{\pi} N_{a_1} q_1 \sin \frac{\pi}{p'} = q_1 E_1 \sin \frac{\pi}{p'} \qquad (15)$$

and the complete tap voltage is

$$e_t = q_1 E_1 \sin \frac{\pi}{p'} [\sin \omega t + k_3 q_3 \sin (3 \omega t + \theta_3 + \pi w)$$
$$+ k_5 q_5 \sin (5 \omega t + \theta_5 + \pi w) + \text{etc.}] \qquad (16)$$

A consideration of the value of $w$ or of the curves of Fig. 5 will show that in the 180° electromotive force the third, seventh, eleventh, etc., harmonics are reversed; that in the 120° electromotive force, the third, ninth, fifteenth, etc., harmonics vanish and the fifth, eleventh, seventeenth, etc., harmonics are reversed; and that in the 60° electromotive force the seventh, ninth and eleventh, the nineteenth, twenty-first and twenty-third, etc., harmonics are reversed.

To reduce these to a more specific basis assume the case of a 60-cycle converter with twelve slots per pole. Then

$$e_{t-180} = q_1 E_1 [\sin \omega t - 0.34 q_3 \sin (3 \omega t + \theta_3) + 0.214 q_5 \sin (5 \omega t + \theta_5) - 0.165 q_7 \sin (7 \omega t + \vartheta_7) + 0.141 q_9 \sin (9 \omega t + \theta_9) - 0.1316 q_{11} \sin (11 \omega t + \theta_{11}) + 0.1317 q_{13} \sin (13 w t + \theta_{13}) - 0.1413 q_{15} \sin (15 \omega t + \theta_{15}) + 0.164 q_{17} \sin (17 \omega t + \theta_{17}) - 0.214 q_{19} \sin (19 w t + \theta_{19}) \ . \ . \ . \ + \text{etc.}] \tag{17}$$

$$e_{t-120} = 0.866 q_1 E_1 [\sin \omega t - 0.214 q_5 \sin (5 \omega t + \theta_5) + 0.165 q_7 \sin (7 \omega t + \theta_7) - 0.1316 q_{11} \sin (11 \omega t + \theta_{11}) + 0.1317 q_{13} \sin (13 \omega t + \theta_{13}) - 0.164 q_{17} \sin (17 \omega t + \theta_{17}) + 0.214 q_{19} \sin (19 \omega t + \theta_{19}) \ . \ . \ . \ + \text{etc.}] \tag{18}$$

$$e_{t-60} = 0.5 q_1 E_1 [\sin \omega t + 0.68 q_3 \sin (3 \omega t + \theta_3) + 0.214 q_5 \sin (5 \omega t + \theta_5) - 0.165 q_7 \sin (7 \omega t + \theta_7) - 0.282 q_9 \sin (9 \omega t + \theta_9) - 0.1316 q_{11} \sin (11 \omega t + \theta_{11}) + 0.1317 q_{13} \sin (13 \omega t + \theta_{13}) + 0.283 q_{15} \sin (15 \omega t + \theta_{15}) + 0.164 q_{17} \sin (17 \omega t + \theta_{17}) - 0.214 q_{19} \sin (19 \omega t + \theta_{19}) + \text{etc.} \ . \ . \ ] \tag{19}$$

With a larger number of slots per pole such as would be employed for a 25-cycle converter, the harmonic coefficients would be reduced, especially for the higher harmonics, see Table II. It is interesting to note that with as small a number of slots per pole as here assumed, 12, the reduction factor does not continue to decrease indefinitely as $m$ increases but actually begins to increase from the thirteenth harmonic up. Also its value for the nineteenth harmonic is more than one-fifth, or three times its value when $N_{sp} = 24$.

It is thus possible to determine easily and accurately any tap voltage, from the harmonic analysis of the flux distribution curve. It is obviously much easier to determine the harmonics of the flux distribution curve with a given degree of accuracy, than it is to determine those of the resultant electromotive force wave, since the former are several times larger than the latter.

*Root mean square tap voltage.* This is obviously,

$$E_t = \frac{q_1 E_1}{\sqrt{2}} \sin \frac{\pi}{p'} \sqrt{1 + k_3^2 q_3^2 + k_5^2 q_5^2 + k_7^2 q_7^2 + \text{etc.}} \tag{20}$$

or, for the special case of twelve slots per pole

$$E_{180} = 0.707 q_1 E_1 \sqrt{1 + 0.116 q_3^2 + 0.0458 q_5^2 + 0.027 q_7^2 + 0.0199 q_9^2 + 0.073 q_{11}^2 + 0.0173 q_{13}^2 + 0.02 q_{15}^2 + 0.027 q_{17}^2 + 0.0458 q_{19}^2 + \text{etc.}} \tag{21}$$

$$E_{120} = 0.613\ q_1\ E_1 \sqrt{1 + 0.0458\ q_5^2 + 0.027\ q_7^2 + 0.0173\ q_{11}^2 + 0.0173\, q_{13}^2 + 0.027\, q_{17}^2 + 0.0458\, q_{19}^2 + \ .\ .\ .\ \text{etc.}} \tag{22}$$

$$E_{60} = 0.354\, q_1 E_1 \sqrt{1 + 0.462\, q_3^2 + 0.0458\, q_5^2 + 0.027\, q_7^2 + 0.0795 q_9 + 0.0173\ q_{11}^2 + 0.0173\, q_{13}^2 + .08\, q_{15}^2 + 0.027\, q_{17}^2 + 0.0458\, q_{19}^2 + \text{etc.}} \tag{23}$$

## VOLTAGE RATIO

*The ratio of brush voltage to tap voltage* is obtained from equations (4a) and (20). It is

$$K_{bt} = \frac{E_{dc}}{E_t} = \frac{\sqrt{2}}{q_1 \sin \frac{\pi}{p'}} \times \frac{(1 + \frac{1}{3} q_{a3} + \frac{1}{5} q_{a5} + \frac{1}{7} q_{a7} + \text{etc.}\ .\ .)}{\sqrt{1 + k_3^2 q_3^2 + k_5^2\ q_5^2 + k_7^2\ q_7^2 + \text{etc}}} \tag{24}$$

or

$$K_{bt} = \frac{\sqrt{2}}{q_1 \sin \frac{\pi}{p'}} K_q \tag{25}$$

where

$$K_q = \frac{(1 + \frac{1}{3} q_{a3} + \frac{1}{3} q_{a3} + \frac{1}{5} q_{a5} + \text{etc.})}{\sqrt{1 + k_3^2\, q_3^2 + k_5^2 q_5^2 + k_7^2 q_7^2 + \text{etc.}}} \tag{26}$$

## THREE-PART POLE.

With a normal flux distribution curve, or with a three-part pole and symmetrical distortion, the $q_b$'s are zero, $q_1 = 1$ and $q_m = q_{am}$. The denominator of $K_q$ will differ little from unity, being always a little greater; for example, with a 30 per cent. third harmonic the denominator is 1.005; with a 15 per cent. third, a 15 per cent. fifth and a 15 per cent. seventh harmonic, the denominator is about 1.002. The numerator, on the other hand, may differ considerably from unity on either side according as the $q_a$'s are positive or negative. With a normal undistorted flux distribution the numerator will be slightly less than unity, and $K_{bt}$ will be slightly less than as given by the usual approximate formula. Any variation in the $q_a$'s, due to a symmetrical distortion, causes a variation in the voltage ratio; but it will also produce a variation in the harmonics of the tap electromotive forces. The relation between these two variations in the case of symmetrical distortion will next be considered.

Assume that the flux distribution curve is completely under control; start with a sinusoidal distribution and add harmonics. First add a third harmonic which will be in phase with or in exact opposition to the fundamental, since for a symmetrical distortion $q_{b_3} = 0$; that is $q_3 = q_{a_3}$. Also assume $N_{sp} = 24$, and a winding of full pitch with interslot connections. Then

$$K_{q_3} = \frac{1+\frac{1}{3}q_{a_3}}{\sqrt{1+0.112\, q_{a_3}^{\,2}}}$$

and the corresponding harmonic in the tap electromotive forces is $k_3\, q_{a_3}$ which is $0.335\, q_{a_3}$ for the 180° electromotive force and zero for the 120° electromotive force.

In curve 3 of Fig. 6, $K_{q_3}$ is shown plotted against $k_3\, q_{a_3}$ for the case in hand; that is, the curve shows the per cent. change in the voltage ratio corresponding to various per cent. magnitudes of the third harmonic in the 180° electromotive force. This harmonic appears with the same per cent. magnitude in the 90° electromotive force and with double this magnitude in the 60° electromotive force, but vanishes in the 120° electromotive force.

The per cent. magnitude of the third harmonic in the flux distribution curve is approximately three times that in the 180° tap voltage.

Curves 7, 11 and 17, of Fig. 6, show for the seventh, eleventh and seventeenth harmonics, the same relation as is shown in curve 3, for the third harmonic.

From these curves it is evident that the several harmonics are almost equally effective in changing the voltage ratio; that is, for a given change in voltage ratio, the resulting harmonic in the tap voltage is of practically the same magnitude whether it be third, fifth, seventh, or higher. It should be noted, however, that to obtain a given change in voltage ratio by means of the higher harmonics, requires a much greater distortion of the flux distribution curve than by means of the lower harmonics, although the resulting electromotive force distortion is approximately the same in the two cases. For example, referring to Fig. 6, to change $K_q$ from 1.0 to 0.9 by the third harmonic, requires a 10 per cent. third harmonic in the 180° electromotive force, which means a 30 per cent. third harmonic in the flux distribution curve; but to produce the same change in $K_q$ by the seventeenth harmonic requires a 12 per cent. seventeenth harmonic in the 180° electromotive force, and $\left(\frac{12}{k_m} =\right)$ 165 per cent. seventeenth harmonic in the flux distribution curve. Such a distortion is out of the question, in fact it is quite obvious that the higher harmonics play a very small part in the voltage ratio or in the distortion of the tap voltage.

Consider now the effect of a combination of harmonics, which

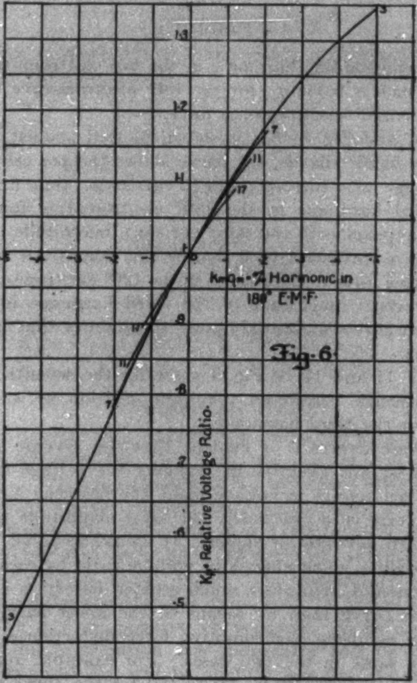


Fig. 6.

corresponds more nearly to the actual conditions. The $q_n$'s must all be of the same sign in order to produce the maximum effect upon $K_q$ for a given electromotive force distortion, and in that case they will have practically the same effect as a single harmonic producing the same electromotive force distortion. For example, consider the following combinations:

(a), $q_{a_3} = 0.60$; and (b), $q_{a_3} = 0.21$, $q_{a_5} = 0.35$, and $q_{a_7} = 0.396$. For (a), $k_3\, q_{a_3} = 0.201$ and $K_q = \frac{1.2}{1.02} = 1.177$; for (b), $k_3\, q_{a_3} = 0.0704$, $k_5\, q_{a_5} = .0711$, $k_7\, q_{a_7} = 0.0585$, $\Sigma k_m\, q_{am} = k_3\, q_{a_3} + k_5\, q_{a_5} + k_7\, q_{a_7} = 0.20$ and $K_q = \frac{1.197}{1.007} = 1.188$. Thus for the same total per cent. (0.20) of harmonics, the per cent. variation of voltage ratio is about the same in the two cases.

It might appear that in the case of several harmonics their maxima would not coincide at any point, and that therefore the "sine deviation" would be less for the same total per cent. of harmonics than in the case of a single harmonic; but if the $q_a$'s are all of the same sign, the harmonics in the 180° electromotive force will be alternately inverted and the central maxima will all coincide, giving the same deviation as for a single harmonic.

If the $q_a$'s are not all of the same sign, the variation in $K_q$ will be appreciably reduced for a given total per cent. of harmonics.

Thus with symmetrical distortion of the flux curve, the $q_a$'s, in order to produce the largest variation in $K_q$ for a given electromotive force distortion, must all be of the same sign; but it makes little difference which harmonics are used.

Starting with a sinusoidal flux curve, the per cent. change in voltage ratio is of about the same magnitude as the total per cent. of harmonics in the 180° electromotive force; but the normal undistorted flux distribution is not sinusoidal. Its harmonics are not large, however, the largest being a negative fifth harmonic of not more than ten or fifteen per cent., which means a fifth harmonic of not more than two or three per cent. in the 180° electromotive force. This would correspond to a point on the curves of Fig. 6, slightly below the origin. Starting thus with negative harmonics in the flux distribution curve, the addition of positive harmonics would, for a given change in $K_q$, give a more nearly sinusoidal 180° electromotive force than would the addition of more negative harmonics; that is, for a given range in $K_q$, the least electromotive force distortion occurs when the mean value of $K_q$ is unity or slightly less.

For example, for a total range of 20 per cent. variation in $K_q$, the least possible harmonics will be about 10 per cent., provided a full pitch winding and interslot connections be employed. With a fractional pitch winding, mid-slot connections, or both, this may be reduced according to the winding pitch and the harmonics employed, see Fig. 4. If it were possible to employ only fifth and seventh harmonics, and if commutation requirements did not prevent the use of a coil pitch as low as 0.83, the two harmonics in question would be reduced to about one-fourth of their full pitch values or to about 2.5 per cent. of the fundamental in the 180° electromotive force. As a matter of fact the fifth harmonic is naturally the most prominent one in a three-part pole symmetrical distortion, and it is not difficult to avoid a large third harmonic, but the use of the fifth harmonic involves much more flux distortion for the same change in voltage ratio, as has already been pointed out.

With the 120° connection the third harmonic disappears, but the fifth harmonic has the same value as in the 180° electromotive force. It is thus less advantageous to use the 120° connection with a three-part pole than with a type of distortion in which the third harmonic predominates.

It is possible to make the third harmonic the most prominent by shortening up the interpolar arc, and thus to take advantage of the fact that the third harmonic disappears in the 120° connection; but this makes the commutating field very steep and the commutation sensitive.

### TWO-PART POLE.

In this case the distortion results in a lateral shifting of the center of gravity of the flux wave and an introduction of cosine terms into the equation for the single conductor electromotive force (equation 3); that is, the $q_b$'s are no longer zero and at least some of the $q$'s are larger than the corresponding $q_a$'s. Unless the $q_b$'s are very large, they will not affect the denominator of $K_q$ (equation 26) appreciably, and $K_q$ will be only a very little smaller than when the $q_b$'s are zero, the same $q_a$'s assumed. But the increase in the $q$'s will increase the per cent. harmonics in the tap voltage, corresponding to a given $K_q$.

A little consideration will show that one of the principal cosine terms introduced by the lateral distortion here considered is that of the fundamental, and that, therefore, $q_1$ $(= \sqrt{1+q_{b_1}{}^2})$ is no longer unity and constant, but increases with the distortion. Thus the first factor in the expression for the voltage ratio, $K_{bt}$ (equation 24), decreases with increasing distortion owing to the increase of $q_1$. If at the same time the $q_a$'s have been increasing positively, the two effects will tend to neutralize, but if the $q_a$'s are decreasing, the two effects are in the same direction and it is obviously possible to obtain a greater change in voltage ratio for a given total per cent. of harmonics in the 180° tap electromotive force than with the symmetrical distortion. Moreover, it will be remembered that $q_m$ is the amplitude of the $m$th harmonic of the flux distribution curve in terms of $a_1$, the amplitude of the fundamental sine term; but the real measure of distortion is the amplitude of the harmonic in terms of the whole fundamental; it is, therefore,

$$q_m \div q_1 = \sqrt{q_{am}^2 + q_{bm}^2} \div \sqrt{1 + q_{b1}^2}$$

which may be considerably smaller than $q_m$, and $\frac{k_m\, q_m}{q_1}$ the real per cent. harmonic may be considerably smaller than $k_m\, q_m$. For example it is quite possible to shift the center of gravity of the flux distribution curve by 40°, which means that $q_1$ is about 1.3 and that the $m$th harmonic in the 180° electromotive force is $0.77\, k_m\, q_m$.

It may be instructive at this point to compare the two-part pole lateral distortion with a shifting of the brushes and a fixed flux distribution. Assume the latter to be sinusoidal, imagine the brushes to be shifted by an angle $\beta$ and disregard commutation difficulties. Imagine the flux distribution curve to be subdivided into two components, one in space phase with the new brush position and in magnitude proportional to cos $\beta$, and the other in quadrature with the brush position and proportional to sin $\beta$. The brush voltage and therefore the voltage ratio will be reduced by the factor cos $\beta$, but there will be no harmonics in the flux distribution curve or in any of the tap voltage waves. This may be described as a method of altering the differential factor of the brush voltage without changing or distorting the tap voltage.

Were it not for commutation difficulties, this would be an ideal method of varying the voltage ratio of converters. The case of extreme two-part pole distortion such as shown in Fig. 7 looks very much like a shift of brushes with notches cut in the flux curves for commutation purposes.

It is thus obvious that the two-part pole distortion affects the voltage ratio in quite a different way from that of the symmetrical distortion, and that this way does not necessarily involve such serious harmonics in the resulting electromotive force wave. This difference may be most easily specified by means of equation 25: the symmetrical distortion affects the voltage ratio only through $K_q$, and there is a fairly definite minimum electromotive force distortion involved in a given change in $K_q$; but the lateral distortion affects the voltage ratio mostly through $q_1$, and were it not for the necessity of the brush notch in the flux curve, $K_q$ might be kept nearly constant and the harmonics largely eliminated. Unfortunately the necessity for the notch or weak field at the brush position does introduce some harmonics but the worst of these is usually the third, and it can be eliminated by employing the double delta connection, or a diametral connection with the transformer primaries connected in star.

There appears to be in the case of the two-part pole, no simple method of determining the minimum electromotive force distortion corresponding to a given change in voltage ratio, but it is evident from the above analysis that it may be considerably less than with the symmetrical distortion of a three-part pole.

As an example consider Fig. 7, which shows a flux distribution curve for extreme distortion calculated from the dimensions of an actual machine. A rough harmonic analysis of this curve gives the following constants.

Table III.

| $m =$ | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 |
|---|---|---|---|---|---|---|---|---|
| $q_{am} =$ | 1. | −0.417 | +0.0438 | +0.0353 | −0.1446 | +0.01434 | +0.0522 | −0.026 |
| $q_{bm} =$ | +0.822 | −0.268 | −0.359 | + .0093 | −0.0084 | −0.064 | +0.069 | −0.043 |
| $q_m =$ | 1.295 | 0.495 | 0.362 | 0.0364 | 0.145 | 0.0657 | 0.0827 | 0.0503 |
| $180° k_m =$ | 1. | 0.3353 | 0.2034 | 0.1477 | 0.1177 | 0.0902 | 0.087 | 0.0786 |
| $180° \frac{k_m q_m}{q_1}$ | 1. | 0.128 | 0.0568 | 0.00415 | 0.0132 | 0.005 | 0.0058 | 0.00305 |
| $120° \frac{k_m q_m}{q_1}$ | 1. | 0 | 0.0568 | 0.00415 | 0 | 0.005 | 0.0058 | 0 |

$k_m$ is taken for full pitch winding, interslot connections 24 slots per pole, and 180° taps. $k_m\, q_m \div q_1$ is the per cent. harmonic in the tap electromotive force.

There are doubtless higher harmonics of appreciable magnitude, but they do not influence the quantities with which we are at present interested. The voltage ratio is (from equation 24)

$$\frac{E_{dc}}{E_{t-180^\circ}} = \frac{\sqrt{2}}{q_1} \; \frac{(1 + \frac{1}{3} q_{a_3} + \frac{1}{5} q_{a_5} + \text{etc.})}{\sqrt{1 + k_3^2\, q_3^2 + k_5^2\, q_5^2 + \text{etc.}}}$$

$$= \frac{\sqrt{2}}{1.295} \; \frac{0.862}{1.016} = \sqrt{2} \times 0.655$$

This ratio is less than two-thirds of the ratio for a sinusoidal flux distribution central between brushes, and just about two-thirds of the ratio with a normal undistorted field. Taking this as the no-load ratio, the increase when the auxiliary pole is fully excited in the positive direction, will be 50 per cent, or the decrease in this ratio for the reverse change will be about 33 per cent.

The total of harmonics in the 180° electromotive force is 21.6 per cent. and in the 120° electromotive force only 7.2 per cent, both of which are considerably less than is possible for the three-part pole and an equal variation in voltage ratio. But it is quite possible that a more careful design of pole faces might result in a yet lower per cent. of harmonics. For example, an increase in the width of the auxiliary pole would decrease the fifth harmonic and thus the per cent. harmonics in the 120° electromotive force.

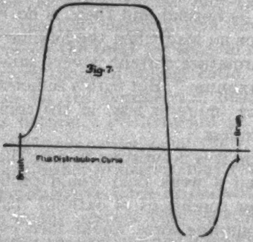


Fig. 7.

The above figures are for full pitch winding and interslot connection. With mid-slot connections and a coil pitch of twenty-three slots the per cents. are reduced to 19 and 6 respectively, and sufficient reduction of pitch would practically wipe out all the harmonics from the 120° electromotive force and all those of the 180° electromotive force except the third. But the conditions cited in this example are extreme and it is quite possible, with a reasonable range of voltage ratio, to reduce the harmonics in the 120° electromotive force to very low figures without employing a coil pitch so low as to endanger commutation. Moreover, these harmonics are of the induced electromotive force and will not appear in full magnitude at the transformer primaries since they will be partly consumed by the small harmonic currents, flowing through the reactance of armature and transformers.

*Damping*. Mr. Lincoln stated in his discussion at the February New York meeting that the result of the harmonics in the induced electromotive force would be harmonic currents which would react upon the field in such a way as partly to prevent the otherwise flux distortion, and thus require greater unbalancing of excitation. This is true, but the use of low resistance squirrel-cage dampers would preserve a constant flux distribution and would relieve the circuit of any considerable damping currents.

*Commutation*. It might seem at first sight that commutation in a field such as shown at the brushes in Fig. 7, would not be satisfactory, but if the direction of rotation of the armature be taken away from the auxiliary poles the armature magnetomotive force will at least partly neutralize the field magnetomotive force in the commutation zone, and the commutation may be even better at some loads than under ordinary conditions. It should be remembered, however, that at full load when the armature magnetomotive force is the greatest the polarity of the auxiliary pole is normal and there is no flux to neutralize, and that at light or no load when the auxiliary pole is reversed as in Fig. 7, the armature current is very small and the flux to be reversed is a maximum. But with a sufficiently low reactance voltage a little flux (more or less) in the commutating zone is comparatively harmless.

In this connection it is interesting to note that a machine with a short air-gap and a weak field would probably have better commutation under conditions of extreme distortion, since the armature magnetomotive force would then even at light load be able to materially reduce the flux in the commutation zone. A saturation of pole tips would also be an aid to this end as well as to the end of eliminating some of the higher harmonics from the flux distribution curve.

The extent to which the winding pitch can be reduced without endangering commutation depends upon many details of design such as reactance voltage, width of brush, length of air-gap, etc., and can only be determined satisfactorily by experiment; the writer therefore hesitates to make a bold guess, although if forced he would place the lower limit at 90 per cent. under reasonably favorable conditions.

*Summary*. With the 180° connection and a large number of slots, an *m*th harmonic in the flux distribution appears in the tap electromotive force, but reduced to about $1/m$th of its per cent. value. Thus the higher harmonics rarely appear in the tap electromotive force unless they are very large in the flux distribution curve. Moreover, the higher harmonics are of little value in changing the voltage ratio, (see equation 24), so that they need have little consideration.

With the 120° connection the third, ninth, fifteenth, etc., harmonics do not appear in the tap electromotive force, and there will be no corresponding harmonic currents set up. This assumes that the flux distribution curves under north and south poles are exactly alike, otherwise there may be a third harmonic even in the 120° electromotive force.

With the diametral connection and the transformer primaries star connected, these harmonics do not appear in the line electromotive force nor their currents in the line.

With three-part poles and symmetrical distortion, there is a definite minimum per cent. of electromotive force harmonics for a given range of voltage ratio and as in this case the fifth harmonic is usually prominent (especially with equal part poles), less advantage can be taken of the fact that the third harmonic vanishes in the 120° electromotive force.

With two-part poles, the total per cent. of electromotive force harmonics for a given range of voltage ratio, may be made considerably less than for the symmetrical distortion, and as the third harmonic is naturally predominant in this case, the employment of the 120° connection, or of the 180° connection with star-connected transformer primaries, may result in the practical elimination of electromotive force or current harmonics.

The conditions in this respect may be still further improved by the use of mid-slot connections and a fractional pitch winding, as far as the latter is consistent with good commutation.

The first part of this paper applies as well to alternators as to synchronous converters; the writer expects shortly to put it into such shape that it will be more useful in the study of alternator wave shape and in the design of alternators.

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# APPLICATION OF STORAGE BATTERIES TO REGULATION OF ALTERNATING-CURRENT SYSTEMS

BY J. L. WOODBRIDGE

The general function of a storage battery in connection with an alternating-current system is the same as in a direct-current system, namely, to relieve the power plant and in some cases the transmission lines of the fluctuations of load, permitting the generating machinery and conductors to be utilized to the greatest advantage and at maximum economy by subjecting them to a steady load equal to the average, instead of a load whose fluctuations in some instances, as in heavy interurban railway work and in many industrial plants, are exceedingly rapid and severe. In many cases where alternating currents are developed, the advantages of a regulating storage battery are even more pronounced than in direct-current service, for the following reasons:

1. Alternating-current generation is particularly applicable to long distance interurban railway work where steam railroad conditions prevail, involving heavy units operating at comparatively infrequent intervals, producing fluctuations of load abnormally high as compared with the average. These conditions are comparable, except on a largely magnified scale, with those obtaining on the four or five car electric roads so common in the early history of electric railways.

2. In many cases alternating current is developed at water-power plants and transmitted for considerable distances, and it is well known that a storage battery affords special advantages in connection with the operation of a water-power supply to which are added the advantages of a practically constant current on the transmission lines.

3. In many such cases of water-power development with alternating-current transmission, power is sold on the maximum demand basis, and the saving in power bills effected by removing the peaks and fluctuations with a storage battery makes the battery installation a very attractive investment.

4. The auxiliary apparatus required in connection with a storage battery adapted for regulating an alternating-current system may also be used for changing the frequency or controlling the power factor.

5. The increasing use of gas engines in steel plants for utilizing the furnace gas offers a large field for the application of storage batteries, and in most of these plants the heavy loads and the large area covered call for alternating-current generation and distribution.

The conditions to be met in the various alternating-current systems include a number of different combinations which may be classified broadly as follows:

### A. GENERATION ENTIRELY ALTERNATING-CURRENT

I. Load wholly direct-current. Distribution by alternating-current transmission lines to direct-current sub-stations.

II. Load wholly alternating-current, polyphase.

III. Load wholly alternating-current, single-phase.

### B. GENERATION AND LOAD PARTLY ALTERNATING-CURRENT AND PARTLY DIRECT-CURRENT

IV. Direct-current fluctuations preponderating.

V. Alternating-current fluctuations preponderating.

Below is given an outline of the methods which have been adopted or suggested for handling each of these cases. In every case it is of course necessary to have converting apparatus for interchangeably transforming alternating and direct currents as well as automatic apparatus for controlling the transfer of energy between the alternating- and the direct-current circuits. Such apparatus is taken up in detail in the latter part of this paper.

I. Under this heading are included systems in which alternating current is generated and transmitted to direct-current sub-stations for supplying a direct-current fluctuating load such as that of the ordinary interurban direct-current trolley system. The early applications of storage batteries to systems of this kind involved the installation of a battery at each of the several sub-stations to regulate the fluctuations of direct-current load at that point. This required nothing more than the ordinary direct-current controlling apparatus. In some recent installations, however, the conditions have been such that it has been found advantageous to concentrate the battery capacity at one point, a single battery being installed arranged to control the total combined fluctuations of load on the entire system. Such an arrangement obviously reduces the first cost for two reasons. First, the total battery capacity required will usually be considerably smaller where the battery is concentrated in this way, inasmuch as the maximum fluctuations of the combined load will ordinarily be less than the sum of the maximum fluctuations occurring at the several sub-stations, since the latter do not occur simultaneously. Second, the cost per unit of capacity of a single large battery will obviously be less than that of a number of smaller installations. This is particularly true of the auxiliary apparatus.

In order to permit of this concentration of the battery capacity it is necessary to select some point for installing the battery, from which the conductors carrying the total output of the generating plant are readily accessible. In many cases a converter station located at the power house itself affords the most suitable location. In other cases where the transmission is wholly in one direction from the power house the nearest sub-station may be selected. In such cases the battery with its regulating booster is connected to the direct-current sub-station bus-bars in the usual manner, but the booster is controlled by means responsive to the total alternating-current output of the generating plant. Its control is accomplished by means of current transformers located in the main alternating-current bus-bars or transmission lines, between the converter station and the generators, whose secondaries will furnish alternating-current to the battery controlling apparatus proportional to the total output of the power station. In some cases current transformers are located in the individual generator circuits, their secondaries being connected in parallel to give a combined output proportional to the total generator load.

By this arrangement the same converters which are required for supplying the local direct-current load on the sub-station are also used for transforming the battery current, and in many cases no greater converter capacity is called for on account of this latter function. For example, the total load on the system may vary from 500 to 3000 kw. with an average of 1500 kw. The direct-current demand on the sub-station where the battery is located may vary from zero to 1500 kw. Converting apparatus must therefore be installed at this sub-station of sufficient capacity to handle a momentary load of 1500 kw. It is evident that with the battery regulating on the total load this converting apparatus will never have to deliver more than 1500 kw. to the sub-station, since this is the total output from the generators and this amount of energy will be supplied to this sub-station only at rare intervals when the total load on the rest of the system is zero. Nor will this converting apparatus be called upon to transmit energy in the reverse direction to a greater amount than 1500 kw. since the total maximum load on the entire system is 2000 kw. of which the main generator is always supplying 1500. At times of maximum total load there will

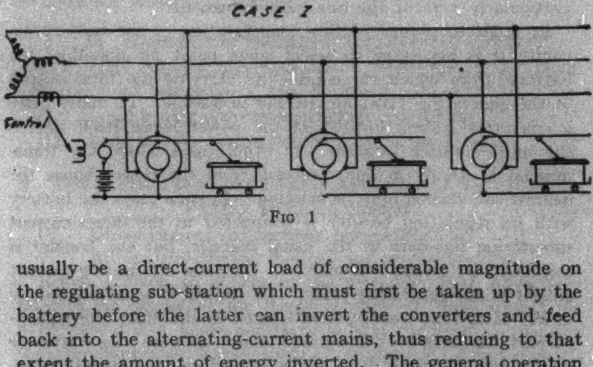

FIG. 1

usually be a direct-current load of considerable magnitude on the regulating sub-station which must first be taken up by the battery before the latter can invert the converters and feed back into the alternating-current mains, thus reducing to that extent the amount of energy inverted. The general operation of the battery in this scheme is to relieve the sub-station of more or less of its direct-current load at times of increased load on the rest of the system, thus preserving a constant load on the generating units. It being necessary on account of the direct-current load to maintain constant voltage on the direct-current bus-bars, a battery booster will be required to cause the battery to charge and discharge, this booster being controlled from the alternating-current circuit. This case is illustrated diagrammatically in Fig. 1.

II. In this case the current is generated and utilized as polyphase alternating current, there being no direct-current circuit. Under these conditions the battery would be located either at the main generating station or in some cases at the center of load, and inasmuch as the entire output of the battery must be converted into alternating current, converting apparatus, either motor-generator sets or synchronous converters, must be provided of sufficient capacity to handle the maximum battery discharge. If a motor-generator set is used for control, the charge and discharge of the battery may be accomplished by varying the voltage of the direct-current machine in response to fluctuations of the alternating-current load. Synchronous converters are undoubtedly preferable for this purpose, particularly if the fluctuations of load are extremely rapid. If a motor-generator is called upon to transfer energy from the battery to the alternating-current circuit it will deliver energy to the latter circuit only after its armature has been driven somewhat ahead of its normal phase position, and owing to the inertia of the armature some appreciable time must elapse after the battery has begun to discharge into the direct-current machine before the alternating-current machine is delivering the equivalent energy to the alternating-current circuit and a time lag is thus introduced. With a synchronous converter this effect is practically eliminated.

With the latter type of machine, however, special means must be provided for varying the direct-current voltage at the battery terminals to compel the battery to charge and discharge. If a standard converter is employed a battery booster will be required to produce this voltage variation. This booster will be provided with field control responsive to the fluctuations of alternating-current load, such controlling apparatus being described below.

On account of the absence of direct-current load, however, a constant direct-current voltage is not required, and in order to dispense with the battery booster a synchronous converter providing for a variable ratio between the alternating- and direct-current voltages has been developed. This machine has been designated the " split-pole " converter owing to the fact that the control of the transformation ratio is brought about by dividing each pole into two or more sections whose excitations are separately controlled. By this means the direct-current voltage of the converter is varied to cause the battery to charge and discharge while the alternating-current voltage is maintained practically constant. This type of machine offers very considerable advantages in the way of simplification and increased efficiency of operation over apparatus involving boosters or motor-generator sets. It is found to be particularly adapted for handling extremely rapid fluctuations of alternating-current load. It must be borne in mind that in dispensing with the booster the means for maintaining a constant-potential direct-current bus-bar is eliminated and any circuit connected directly to the battery terminals will be subject to more or less variation of voltage due to the charge and discharge of the battery. This case is illustrated in Fig. 2.

III. In this case power is generated as alternating current and is supplied to a single-phase circuit. One of the most noted examples of this class of installation is found at the frequency-changing station of the Spokane & Inland Ry. Co. at Spokane, Washington. The equipment of this station includes four frequency- and phase-changing motor-generator sets, each set consisting of three direct connected machines, viz., a 60-cycle, 3-phase induction motor of 1000 h.p. capacity, receiving power from the incoming transmission line; a 1000-kw., single-phase, 25-cycle, 2200-volt generator, delivering current to the railroad; and a 750-h.p., 500-volt, direct-current machine, which is connected to the battery and acts as a generator or a motor when the battery is respectively charging or discharging. The battery consists of 275 cells having a capacity of 1920 amperes at the one-hour rate, and is provided with two motor driven boosters which may be operated in parallel. The boosters are controlled by apparatus which responds to the current in the incoming 60-cycle transmission line in such a way that small variations of this current vary the booster voltage, thus causing the battery to charge from or discharge into the direct-current

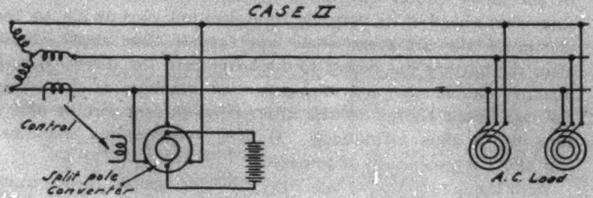

FIG. 2

machine to absorb the fluctuations of load on the single-phase circuit. This is one of the cases in which the financial results from a battery installation may be very clearly demonstrated, inasmuch as the power for the operation of the railway system is purchased on the maximum demand basis, and it is estimated that the reduction in the power bills effected by the battery in relieving the transmission line of load fluctuations will be sufficient to repay the initial investment in about three years. This application is illustrated in Fig. 3.

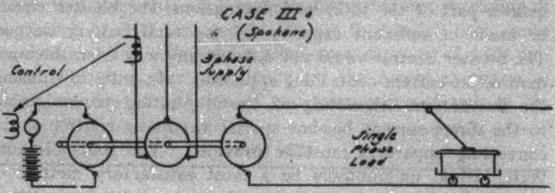

FIG. 3

Instead of the scheme above described it will be quite practicable to utilize the split-pole converter operating as a single-phase machine connected to the single-phase circuit with suitable transformers. The output of the battery will then be delivered to the railway circuit without the intervention of mechanical transmission, and the efficiency on discharge and therefore the net alternating-current output for a given battery discharge will be greater. This is illustrated in Fig. 4.

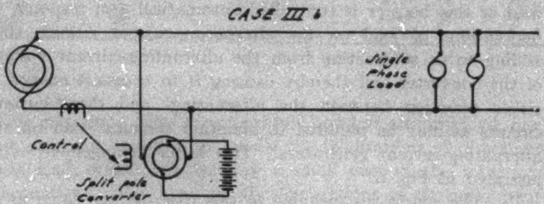

FIG. 4

IV. This and the following case include systems in which both alternating-current and direct-current generators are operated to supply a load which is partly alternating- and partly direct-current, the two circuits being interconnected by suitable converting apparatus. In case IV, the fluctuations of the direct-current load preponderate, and inasmuch as the direct-current bus-bar must ordinarily be maintained at constant voltage a battery booster is required, sufficient at least for the direct-current fluctuations. Since these latter constitute the greater part of the total load fluctuations, the booster should be made of sufficient capacity for the total battery output. The booster control would not differ in any way from the standard direct-current controlling apparatus. In order to transmit the fluctuations originating on the alternating-current circuit to the direct-current bus-bar special automatic control of the converting apparatus must be provided. The split-pole converter would undoubtedly be a most satisfactory method of providing this control, and inasmuch as the direct-current bus-bar voltage is practically constant only a very small change in ratio of conversion would be necessary, just sufficient to overcome the internal drop in the converter and static transformers.

Another method of providing for this automatic control of the converting apparatus consists in mounting on the shaft of the converter an alternating-current booster whose windings are connected in series between the alternating-current terminals of the converter armature and the collector rings. The field of this booster is controlled automatically in response to fluctuations of load on the alternating-current circuit, thus adding to or subtracting from the alternating-current voltage of the converter and thereby causing it to transmit energy in either direction between the alternating- and direct-current circuits as may be required to maintain constant load on the alternating-current generators. This latter arrangement is illustrated in Fig. 5.

V. The conditions included in this case are the same as in case IV except that the alternating-current load fluctuations preponderate. Inasmuch as the direct-current bus-bar voltage must be maintained constant a battery booster is required of sufficient capacity to handle the fluctuations of direct-current load. These fluctuations being comparatively small this booster capacity may be reduced to a minimum provided the fluctuations of alternating-current load are transmitted directly to the battery terminals instead of to the direct-current bus-bars. This latter may be accomplished by means of the split-pole converter which in this case is connected between the alternating-current circuit and the battery terminals, and is so controlled as to transmit directly to the battery the fluctuations of load originating on the alternating-current circuit. This is the scheme which has been adopted for controlling the load fluctuations at the electric power plant of the Indiana Steel Company, at Gary, Indiana.

For this plant there is being installed a battery consisting of two series of cells arranged to operate in parallel, each series consisting of 125 cells having a one-hour capacity of 4320 amperes. Provision has been made for the future extension of this plant by the addition of two more series of cells of the same capacity. Two direct-current boosters are provided, having sufficient capacity to handle the fluctuations of direct-current load, which will be only a small part of the total load fluctuations. For handling the fluctuations of alternating-current load a split-pole converter of 2000 kw. capacity is being installed, designed to provide a range of direct-current voltage from a minimum of 200 to a maximum of 300 volts with constant alternating-current voltage. The regulating field of this converter will be controlled by a special alternating-direct-current exciter, designed as described hereinbelow. Provision has been made for a second converter of the same design and capacity. This case is illustrated in Fig. 6.

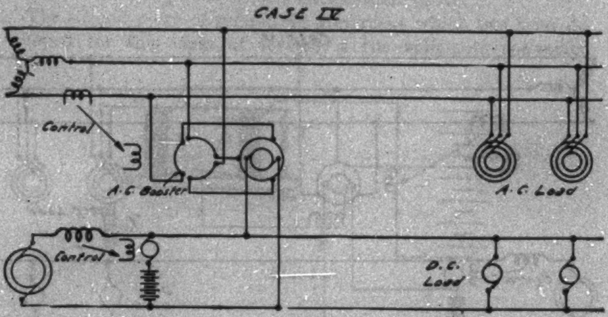

FIG. 5

*Auxiliary apparatus.* Under this heading are described three pieces of auxiliary apparatus which have been developed for controlling the operation of a battery in connection with an alternating-current circuit.

The first of these devices, the carbon regulator, calls for only passing notice, as its general design and operation are well known in connection with direct-current regulating plants. It is shown diagrammatically in Fig. 7, in which $x$ and $y$ are two piles of carbon discs subjected to variable pressure by means of the lever, $L$, which is pivoted between the two piles in such a way that any motion of this lever will increase the pressure on one pile and decrease that on the other. At one end of the lever is an adjustable spring, $T$, while from the other end is suspended the iron core of a solenoid, $S$, which carries the current

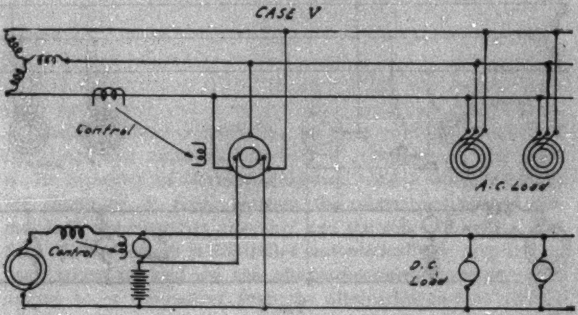

FIG. 6

to be regulated, or a current proportional thereto. The two carbon piles are electrically connected in series across the battery, $B$, while the field coil, $F$, which is to be controlled, is connected between a point in the circuit between the two carbon piles and the middle point of the battery. The variation of resistance in the two piles due to change of pressure causes a flow of current in one direction or the other through the field coil, $F$, which is therefore made responsive to the current in the solenoid, $S$. The application of the regulator to alternating-current control involves the substitution of an alternating-current solenoid for the usual direct-current coil. In those installations where the power factor is normally maintained approximately at unity, such as the usual alternating-current generating plant supplying current to converter sub-stations for direct-current railway service, a single coil supplied with alternating current proportional to the current output of the alternators will give entirely satisfactory results, this current being practically proportional to the true watt output of the machines. If, however, the power factor is normally considerably less than unity or if it is subject to wide variations, it may be necessary to control the carbon regulator by means responsive to the energy component of the current and two coils may be used, one of which will produce a constant magnetic flux, while the other carries current which is in phase with the flux at unity power-factor, or whose energy component is in phase with the flux at power-factors other than unity.

The second piece of regulating apparatus which has been developed for this class of service is the split-pole converter.

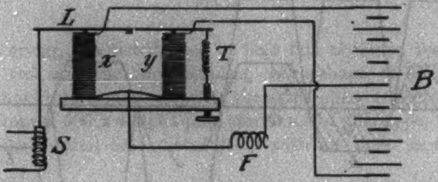

FIG. 7

This machine has already been mentioned in a recent paper before this Institute, but I wish to take up somewhat more in detail certain points in reference to the theory of its operation and the detail of its design.

As originally suggested this type of machine was constructed with each pole sub-divided into three parallel sections with suitable windings for varying the relative excitation of the three sections, the object being to secure a variation of direct-current voltage while maintaining a constant alternating-current voltage. The theory upon which this design was based may be illustrated by reference to Fig. 8, in which is shown an assumed distribution of field flux around the periphery of the armature. The line, *A B*, represents the developed armature periphery, the direct current brushes being located at *A* and *D*. The lines *a*, *b*, and *c*, represent the field strength of the three sections of one pole and the lines *d*, *e*, and *f* that of the other pole under normal conditions of excitation. The result of this excitation will be a certain ratio between alternating- and direct-current voltage. If, now, the excitation of the outer pole sections *a*, *c*, *d*, and *f*, be increased, and that of the middle sections *b*, and *e*, be decreased, the field distribution may then be represented as the resultant of the auxiliary field *g*, *h*, *i*, *j*, *k*, and *l*, superposed upon the normal field. If, now, we consider the electromotive force developed in a section of the armature between the points *P*, and *Q*, which may be taken to represent two of the three phase taps located 120° apart, it will be seen that the auxiliary field will have absolutely no effect on the voltage in this section at any point in the revolution; for the sum of the shaded areas *x*, and *z*, is always equal and opposite to the shaded area *y*. The auxiliary field therefore interposes into the armature section between the points *P*, and *Q*, equal and opposite amounts of field flux, which exactly neutralize each other in the generation of electromotive force between *P*, and *Q*. The effect however of the auxiliary field on the direct-current voltage between the points of brush contact *A*, and *D*, is to produce an increase in that voltage for the reason that between these two points there are two areas of positive flux and only one area of negative flux due to the auxiliary field. Theoretically, therefore, this auxiliary field would produce an increase or decrease in the direct-current voltage without any effect whatever on the magnitude or wave shape of the alternating voltage, between the points *P*, and *Q*, provided these points are spaced 120° apart.

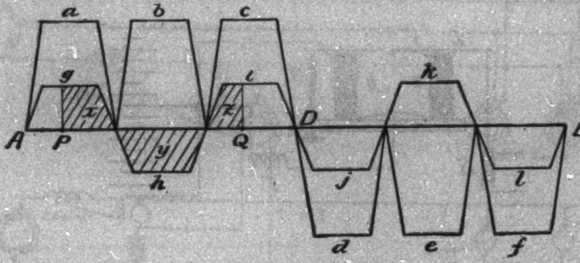

FIG. 8

Practically, however, it is necessary to allow a neutral area of zero field strength at the points $A$, and $D$, for commutation. This modification produces some disturbance of the wave shape of the alternating counter electromotive force, which, however, is not sufficient to interfere with the practical operation of the machine. In Figs. 9 to 14 inclusive, are shown oscillograph records giving the distribution of field flux obtained by an exploring coil and the corresponding wave shape of alternating electromotive force across two of the three phase collector rings, taken from a 500 kw. split-pole converter of this type. Fig. 9 shows the normal field distribution with all three sections of the pole equally excited and Fig. 10 is the corresponding wave shape of electromotive force; direct-current voltage 250. Fig. 11 shows the field distribution with the outer sections increased and the middle section reduced in excitation, while Fig. 12 shows the corresponding wave shape of electromotive force; direct-current voltage 280. Fig. 13 shows the field distribution

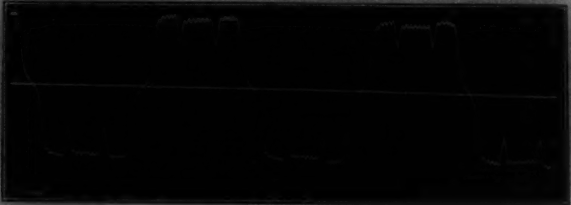

FIG. 9

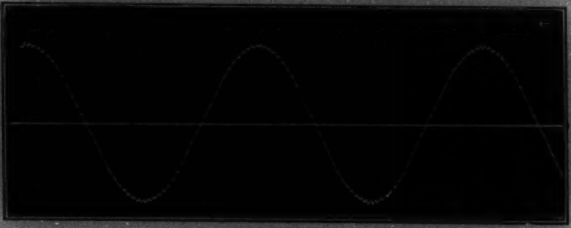

FIG. 10

with the outer sections weakened and the middle section strengthened, and Fig. 14 shows the corresponding wave shape of electromotive force; direct-current voltage 232. It will be noted that the difference in the wave shapes for these three different conditions of field excitation is scarcely perceptible. The alternating electromotive force was held constant throughout.

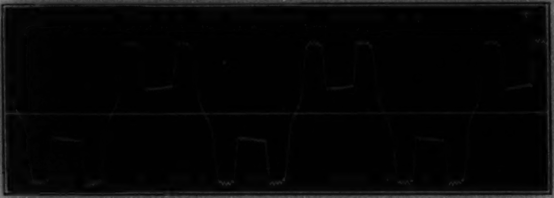

Fig. 11

In a later development of the split-pole converter suggested by Mr. J. L. Burnham, only two pole sections are employed. One of these has a pole arc covering a considerable portion of the total pole pitch, and constitutes the principal pole, while the other covers a smaller arc and is used as an auxiliary or regulating pole. A simple explanation of the theory of this machine may be had by reference to Figs. 15 and 16. In Fig. 15 the line, $O P$, represents the alternating voltage developed by the principal pole section. The line, $O F$, may be taken to represent in amount and phase position the electromotive force developed by the auxiliary pole, these two electromotive forces being displaced by the angle, $\rho$, which represents the angle between the

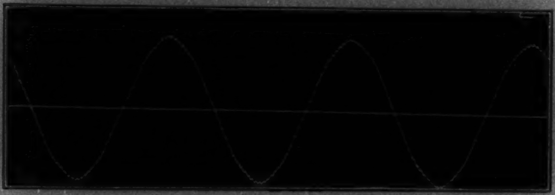

Fig. 12

axes of the two fields. The line, $O R$, will then represent the resultant alternating electromotive force. If the excitation of the auxiliary field is zero, the line, $O P$, will represent the alternating electromotive force. It will be noted that the line, $O R$, is but very little longer than the line $O P$. The direct-current electromotive force will be represented by the algebraic sum of $O P$, and $O F$. With zero excitation of the auxiliary pole this direct-current electromotive force will be represented by $O P$, while with an excitation corresponding with the line $O F$, the direct-current electromotive force will be represented by $O D$. If the main field excitation is reduced to $O P'$, when the auxiliary field has an excitation corresponding with $O F$, the resultant alternating electromotive force will be represented by $O R'$, equal to $O P$, while the direct-current electromotive force will be represented by $O D'$. It will thus be seen that the direct-current electromotive force has been increased from $O P$ to $O D'$ without any change in the magnitude of the alternating

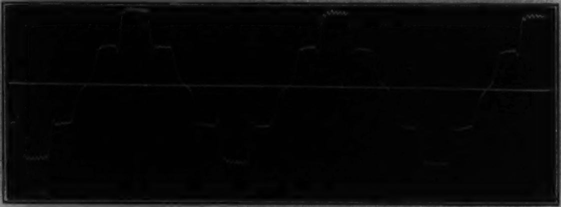

FIG. 13

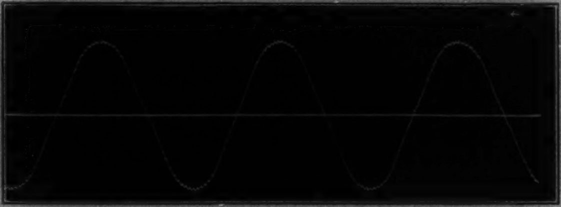

FIG. 14

current electromotive force. If the auxiliary pole be given an initial negative excitation corresponding with the line $O F_0$, such that the resultant $O R_0$ is at right angles to $O F_0$, then any variation of excitation of the auxiliary pole on either side of this point will produce a minimum change in the alternating electromotive force, provided the main field excitation is maintained constant, or will require the least variation in the excitation of the main field to maintain constant alternating electromotive force. Thus if the negative excitation of the auxiliary field be decreased to $F_1$, the resultant alternating electromotive force will be represented by $O R_1$, while if the negative excitation of the auxiliary pole be increased to $F_2$, the alternating electromotive force will be represented by $O R_2$. The corresponding direct-current electromotive forces will be represented by $O D_0$, $O D_1$, and $O D_2$, respectively. For hand control it is of course permissible to vary the excitation of both the main and auxiliary fields, in order to vary the direct-current voltage without disturbing the power-factor. With automatic control it is, however, very desirable to limit the control to a single field coil; and to accomplish this with minimum disturbance to the power factor, it is necessary to work on either side of the point $F_0$ which represents the mean excitation of the auxiliary pole. In Fig. 16 are illustrated the results obtained by designing the machine with a pitch of 90° between the main and auxiliary pole sections. In this case the mean excitation of the auxiliary pole for minimum change in the alternating-current electromotive force is zero, the excitation of this section being varied on either side of zero to produce a change of direct-current electromotive force above and below the mean. It can

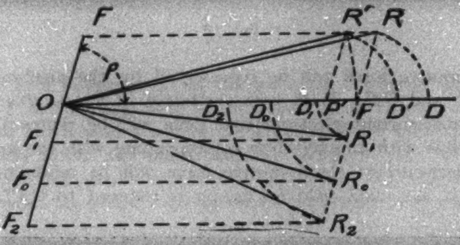

FIG. 15

be readily shown that if the lines $O F_1$, and $O F_2$, are each equal to 20 per cent. of the line $O P$, corresponding with a variation in direct-current electromotive force of 20 per cent. above and 20 per cent. below the mean, the lines $O R_1$, and $O R_2$, will be about 2 per cent. greater than the line $O P$, resulting in a total variation of 1 per cent. in the alternating electromotive force on either side of the normal.

In addition to the change in direct-current voltage it will be noted that a change in the phase position of the resultant alternating electromotive force is brought about by varying the excitation of the auxiliary pole section. If this pole section is made the trailing section, this shifting of the phase position will coöperate with the change in direct-current voltage in bringing about a quick transfer of energy between the battery and the alternating-current circuit, by advancing the phase of the alternating-current voltage, thus causing the converter to deliver energy to the alternating-current circuit at the same time that the direct-current voltage is reduced and energy is thus taken from the battery.

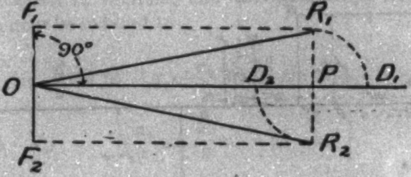

FIG. 16

The effect of the two-section split-pole construction on the wave shape of the alternating electromotive force may be determined in the following manner. Referring to Fig. 17, the line $A D B$ represents as before the developed periphery of the armature, the ordinate $f$ representing the field density at any point, this ordinate having the values $b$, and $c$, at the face of the main and auxiliary pole sections respectively. A neutral space of 30° is allowed for commutation and the pole section pitch is taken at 90° which requires a space of 30° between the main and auxiliary pole sections. This leaves 120° for the combined arc of the two pole sections. Assuming that a variation of direct-current voltage from 20 per cent. above to 20 per cent.

below the mean is desired, and that the maximum density in the two pole sections is to be approximately the same, the arc of the auxiliary pole section should be about 20 per cent. of that of the main section. I have therefore shown the main section covering 100° of arc and the auxiliary section 20°.

Let $\theta$ represent the angular distance of any point on the circumference of the pole faces from the neutral point $A$ which is taken as the origin.

Let $f$ represent the ordinate corresponding with the field density at that point.

Let $X\,Y$ represent any section of the armature, having an angular span $\beta$.

Let $\phi$ equal the angular distance of the center point of the armature section $X\,Y$ from the origin $A$ at any instant in the revolution of the armature.

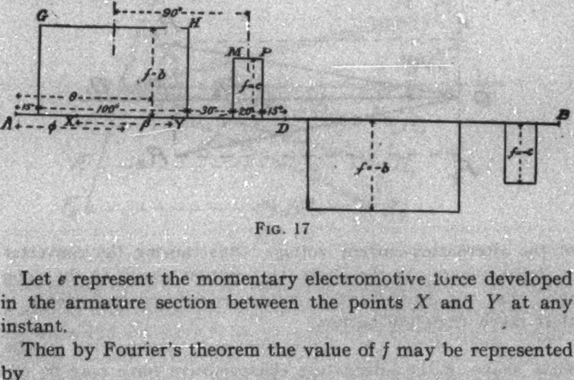

FIG. 17

Let $e$ represent the momentary electromotive force developed in the armature section between the points $X$ and $Y$ at any instant.

Then by Fourier's theorem the value of $f$ may be represented by

$$f = a_1 \sin(\theta - \alpha_1) + a_3 \sin 3(\theta - \alpha_3) + a_5 \sin 5(\theta - \alpha_5) + \ .\ .\ . + a_n \sin n(\theta - \alpha_n) \qquad (1)$$

Also we have

$$e = k \int_{\phi - \frac{\beta}{2}}^{\phi + \frac{\beta}{2}} f\, d\theta \qquad (2)$$

from which, by substituting the value of $f$ in (1) and integrating we have

$$e = k \left\{ a_1 \left[\cos\left(\phi - \frac{\beta}{2} - \alpha_1\right) - \cos\left(\phi + \frac{\beta}{2} - \alpha_1\right)\right] + \frac{a_3}{3}\left[\cos 3\left(\phi - \frac{\beta}{2} - \alpha_3\right) - \cos 3\left(\phi + \frac{\beta}{2} - \alpha_3\right)\right] + \frac{a_5}{5}\left[\cos 5\left(\phi - \frac{\beta}{2} - \alpha_5\right) - \cos 5\left(\phi + \frac{\beta}{2} - \alpha_5\right)\right] \; . \; . \; . + \frac{a_n}{n}\left[\cos n\left(\phi - \frac{\beta}{2} - \alpha_n\right) - \cos n\left(\phi + \frac{\beta}{2} - \alpha_n\right)\right] \right\}$$

in which $k$ is a constant depending upon the design of the machine, the speed of rotation, and the units employed. This expression may be reduced to

$$e = 2\,k \left\{ a_1 \sin\frac{\beta}{2} \sin\left(\phi - \alpha_1\right) + \frac{a_3}{3} \sin\frac{3\beta}{2} \sin 3\left(\phi - \alpha_3\right) + \frac{a_5}{5} \sin\frac{5\beta}{2} \sin 5\left(\phi - \alpha_5\right) \; . \; . \; . + \frac{a_n}{n} \sin\frac{n\beta}{2} \sin n\left(\phi - \alpha_n\right) \right\} \qquad (3)$$

It will be noted that the expression within the brackets consists of the fundamental sine wave $a_1 \sin\frac{\beta}{2} \sin(\phi - \alpha_1)$ upon which is superposed a series of harmonics of the general form $\frac{a_n}{n} \sin\frac{n\beta}{2} \sin n(\phi - \alpha_n)$ The coefficient of each of these harmonic terms is made up of two factors, namely $\frac{a_n}{n}$ and $\sin\frac{n\beta}{2}$ whose product will determine the magnitude of the harmonic. Let us first consider the factor $\frac{a_n}{n}$. In order to determine the value of $a_n$, multiply both members of equation (1) by $\sin n\theta\, d(n\theta)$ and integrate between the limits $\theta = o$ and $\theta = \pi$. The second member will then consist of a series of terms of the form $\int_0^{\pi} a_m \sin m\,(\theta - \alpha_m) \sin n\,\theta\, d\,(n\,\theta)$.

It can be shown that $\int_0^\pi a_m \sin m\,(\theta - \alpha_m) \sin n\,\theta\, d\,(n\,\theta) = o$ when $m$ and $n$ are unequal odd integers. Every term in the second member of the equation therefore reduces to zero except the one term in which $m$ equals $n$ and the equation reduces to

$$\int_0^\pi f \sin n\,\theta\, d\,(n\,\theta) = \int_0^\pi a_n \sin n\,(\theta - \alpha_n) \sin n\,\theta\, d\,(n\,\theta) = \frac{n\,\pi\, a_n \cos n\,\alpha_n}{2} \qquad (4)$$

To eliminate $\alpha_n$ assume the zero point, or origin from which the angular measurements are made, moved forward along the periphery of the pole face by an angle $\frac{\pi}{2n}$ and let $\theta'$ represent the angular distance of any point on the pole faces from this new origin. $\alpha_n$ will then become $\alpha_n - \frac{\pi}{2n}$ and equation (4) becomes

$$\int_0^\pi f \sin n\,\theta'\, d\,(n\,\theta') = \frac{n\,\pi\, a_n \cos\left(n\,\alpha_n - \frac{\pi}{2}\right)}{2} = \frac{n\,\pi\, a_n \sin n\,\alpha_n}{2} \qquad (5)$$

Combining (4) and (5) by squaring and adding we have

$$a_n = \frac{2}{n\pi} \sqrt{\left\{\int_0^\pi f \sin n\,\theta\, d\,(n\,\theta)\right\}^2 + \left\{\int_0^\pi f \sin n\,\theta'\, d\,(n\,\theta')\right\}^2} \qquad (6)$$

The value of the expression $\int_0^\pi f \sin n\,\theta\, d\,(n\,\theta)$ can readily be obtained from the flux distribution. Where $f$ is a succession of constant values as in Fig. 17, the integration gives

$$-f \cos n\,\theta \Big|_{\text{limit}}^{\text{limit}}$$

For the fundamental wave $n = 1$, and the value of the first integral under the radical sign may be derived as follows from the data given in Fig. 17;

| Limits, $\theta$ | $f$ | Integral | Value |
|---|---|---|---|
| 0° to 15° | $o$ | | |
| 15° to 115° | $b$ | $-b\,(\cos 115° - \cos 15°)$ | $+1.3885\,b$ |
| 115° to 145° | $o$ | | |
| 145° to 165° | $c$ | $-c\,(\cos 165° - \cos 145°)$ | $+\ .147\,c$ |
| 165° to 180° | $o$ | | |
| | | Total | $(1.3885\,b + .147\,c)$ |

For the second integral assume the origin moved 90° ahead and proceed as above.

| Limits, $\theta'$ | $f$ | Integral | Value |
|---|---|---|---|
| 0° to 25° | $b$ | $-b\,(\cos 25° - \cos 0°)$ | $+.0937\,b$ |
| 25° to 55° | $o$ | | |
| 55° to 75° | $c$ | $-c\,(\cos 75° - \cos 55°)$ | $+.315\,c$ |
| 75° to 105° | $o$ | | |
| 105° to 180° | $-b$ | $+b\,(\cos 180° - \cos 105°)$ | $-.7412\,b$ |
| | | Total | $-.6475\,b + .315\,c$ |

Substituting these two values in (6) we have

$$a_1 = \frac{2}{\pi}\sqrt{(1.3885\,b + .147\,c)^2 + (-.6475\,b + .315\,c)^2},$$

or

$$a_1 = \frac{2}{\pi}\sqrt{2.347\,b^2 + .121\,c^2} \tag{7}$$

If $c = o$ $\qquad a_1 = .975\,b$
If $c = +b$ or $-b$, $a_1 = 1.000\,b$

Thus we have a variation of 2½ per cent. in the magnitude of the fundamental sine wave of electromotive force with a 40 per cent. change in the direct-current voltage.

To determine the value of $a_5$ we have $n = 5$. Proceeding as above:

| Limits, $\theta$ | $f$ | Integral | Value |
|---|---|---|---|
| 0° to 15° | $o$ | | |
| 15° to 115° | $b$ | $-b\,(\cos 575° - \cos 75°)$ | $1.078\,b$ |
| 115° to 145° | $o$ | | |
| 145° to 165° | $c$ | $-c\,(\cos 825° - \cos 725°)$ | $+1.255\,c$ |
| 165° to 180° | $o$ | | |
| | | Total | $1.078\,b + 1.255\,c$ |

Moving origin 18° ( $= \pi/2n$) ahead,

| Limits, $\theta'$ | $f$ | Integral | Value |
|---|---|---|---|
| 0° to 97° | $b$ | $-b\,(\cos 485° - \cos 0°)$ | $1.574\,b$ |
| 97° to 127° | $o$ | | |
| 127° to 147° | $c$ | $-c\,(\cos 735° - \cos 635°)$ | $-.879\,c$ |
| 147° to 177° | $o$ | | |
| 177° to 180° | $-b$ | $+b\,(\cos 900° - \cos 885°)$ | $-.034\,b$ |
| | | Total | $1.540\,b - .879\,c$ |

From which

$$a_5 = \frac{2}{5\pi}\sqrt{3.532\,b^2 + 2.347\,c^2} \qquad (8)$$

$$\text{If } c = o \qquad a_5 = .239\,b$$
$$\text{If } c = +b \text{ or } -b,\ a_5 = .308\,b$$

By the above method the value of $a_n$ for any harmonic term for any type of synchronous machine may be determined when the field distribution is known. (For a more general solution of the two-sectional pole type, see Appendix.)

Turn now to the other factor in the coefficient, namely $\sin\frac{n\beta}{2}$. The angle $\beta$ represents the angular span included between two alternating-current taps from the armature to the collector rings. When this angle is known this factor in the coefficient is determined. For the ordinary diametric connection we have $\beta = \pi$ and $\sin\frac{n\beta}{2}$ is always ± 1, $n$ being an odd integer, and it can be shown that when $\beta = \pi$, each harmonic in the series is passing through a maximum value with respect to the fundamental. By making $\beta = \frac{2\pi}{3}$, $\sin\frac{3\beta}{2} = 0$, and the third harmonic disappears. Likewise all the multiples of the third harmonic are reduced to zero. This corresponds with the ordinary three-phase delta connection. With this value of $\beta$ we have

$$\sin\frac{n\beta}{2} = \pm\tfrac{1}{2}\sqrt{3}$$

for all values of $n$ except multiples of three. The ratio to the fundamental, of all harmonics except the third and its multiples, will therefore be the same as with the diametric connection.

The third harmonic and its multiples may however be similarly suppressed by star-connecting the primaries of the statics. By doing this the value of $\beta$ may be chosen with reference to some other harmonic than the third. By making $\beta = .8\,\pi$ we have $\sin\frac{5\beta}{2} = 0$ and the 5th harmonic disappears. By making $\beta = \frac{6\pi}{7}$, $\sin\frac{7\beta}{2} = 0$ and the 7th harmonic disappears. By assuming a value for $\beta$ intermediate between $.8\,\pi$ and $\frac{6\pi}{7}$, say $0.82\,\pi$, we have $\sin\frac{5\beta}{2} = 0.1564$ and $\sin\frac{7\beta}{2} = 0.397$, and both the 5th and 7th harmonics are reduced to small percentages of their maximum values.

In Fig. 18 is illustrated a combination designed to suppress the third harmonic and reduce the 5th and 7th to a minimum as above described. The armature $A$, of the converter is provided with alternating-current taps dividing it into three phase-sections, each spanning an angle of $0.82\,\pi = 147° 36'$. The three phase-sections are however displaced by angles of 120°, and can therefore be independently connected across the secondaries of the statics whose primaries are star-connected to the three-phase circuit as shown.

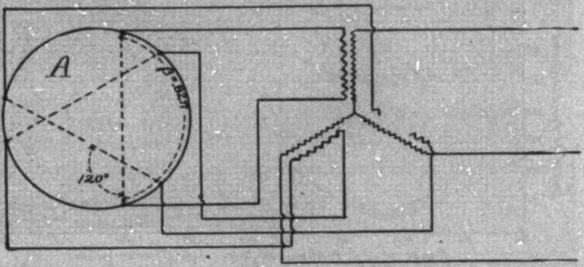

FIG. 18

From equation (3) it will be seen that the ratio of the amplitude of any harmonic to that of the fundamental is

$$\frac{a_n \sin\frac{n\beta}{2}}{a_1 \sin\frac{\beta}{2}}$$

Substituting in this the values of $a_1$ and $a_5$ as given in equations (7) and (8) and similarly determining the value of this ratio for the 7th harmonic, the values of these two harmonics in proportion to the fundamental will be given in terms of the two field densities $b$ and $c$. The direct-current voltage will be proportional to the total field flux, *i.e.*, to $b + .2\,c$ (the smaller pole section arc being 20 per cent. of the greater). From these data the curves shown in Fig. 19 have been plotted, showing the ratio of the 5th and 7th harmonics to the fundamental for various direct-current voltages covering a range of 20 per cent. on each side of the mean. In the curves to the left the diametric connection has been assumed; the same ratios would hold for three-phase delta connection. In the curves to the right the relative values of the same harmonics are given, using the scheme of connection as shown in Fig. 18. In the first case the maximum values of the 5th and 7th harmonics are seen to be 6.2 per cent. and 2.5 per cent. of the fundamental, respectively, while in the latter case they are both reduced to a maximum of 1 per cent. of the fundamental.

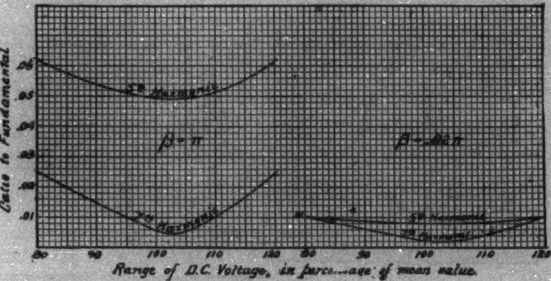

FIG. 19

In Fig. 20, is shown the resultant wave shape obtained by combining the fundamental with the 5th and 7th harmonics, the maximum values of the latter being taken, corresponding with minimum direct-current voltage and diametric connection (see Fig. 19). In Fig. 21, the wave shape is given for the same conditions except that the connections are as shown in Fig. 18 ($\beta = 0.32\,\pi$). In these curves, only the 5th and 7th harmonics have been considered. The 3d and 9th are eliminated by star-connecting the static primaries, and those of higher frequency may be ignored.

The scheme shown in Fig. 18, produces some increase in the heating developed in the armature winding of the converter as compared with the diametric connection. In Fig. 22, curves have been plotted showing this comparison. By reference to these curves it will be seen that the mean $I^2 R$ loss has been increased about 12 per cent., while the maximum loss in any single bar is about 50 per cent. greater than with the diametric connection. The maximum heating per slot is however increased only about 10 per cent. since the two bars in which the heating is maximum are not located in the same slot. These curves are based on field distribution corresponding to the minimum ratio of direct- to alternating-current electromotive force, the value of $c$ in equation (7) being taken as $-b$. This voltage ratio

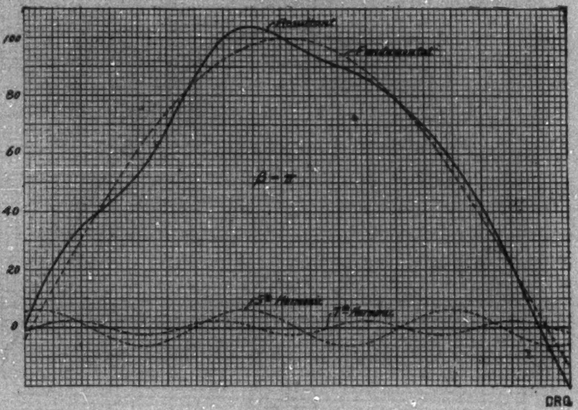

Fig. 20

has of course a material effect on the armature heating since it fixes the ratio between the superposed alternating and direct currents in the armature winding. The curve showing the distribution of heating with diametric phase connection in Fig. 22 is therefore somewhat different from that corresponding to a converter of normal ratio. For intermittent service, such as would be involved in storage battery regulating work, the average heating of the armature winding will usually be of minor importance, as the design of the machine would ordinarily be determined by other considerations, such as commutation at maximum momentary output and flux distribution. Thus the scheme shown in Fig. 18 would appear to offer no appreciable disadvantages. Furthermore, this increase in heating will be at least partially offset by the reduced losses due to the elimination of high frequency currents superposed on the fundamental.

The third piece of auxiliary apparatus which I will describe is an exciter designed to control the regulating field of a booster or split-pole converter in response to variations of load on an alternating-current circuit. This machine is illustrated in Fig. 23, and as there shown consists of an armature, *B*, provided with a bi-polar winding revolving in a four-pole field frame. This armature is connected by suitable collector rings (not shown in the drawing) to the secondary windings of three current transformers $T_1$, $T_2$, $T_3$, whose primaries are connected in series with the alternating-current circuit 1, 2, 3, supplied by a source, *A*, whose load is to be controlled. The alternating current thus transmitted through the armature winding would, if the latter were stationary, produce a revolving field proportional to the output from the source, *A*. The armature is, however, rotated by means of a synchronous motor in the opposite direction to that of the field rotation so as to hold this field stationary in space. There will result a stationary field whose axis is in the line of the arrow $K_1$. A commutator, *C*,

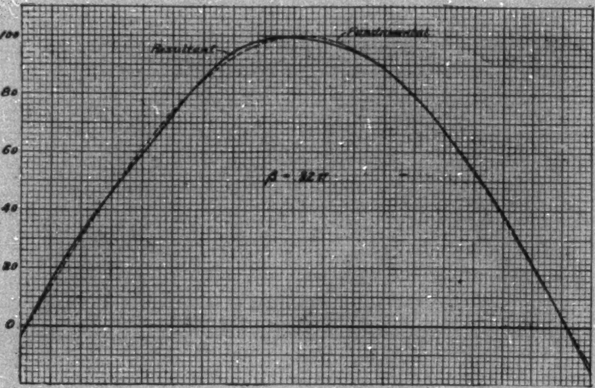

FIG. 21

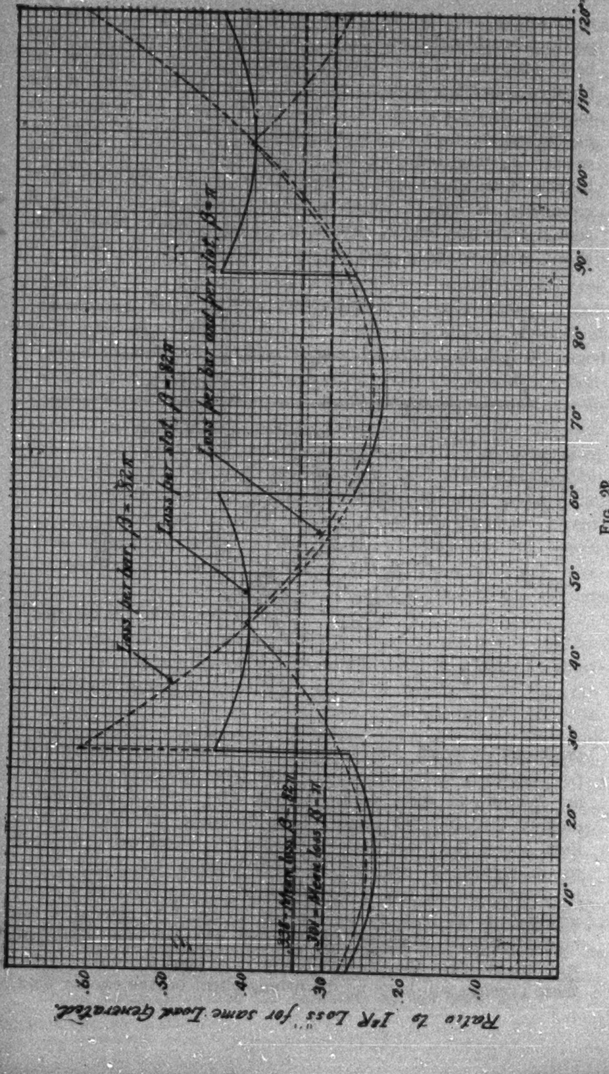
Loss per bar, β = .82π
Loss per slot, β = .82π
Loss per bar and per slot, β = π
.338 – Mean loss β = .82π
.301 – Mean loss β = π
.60
.50
.40
.30
.20
.10
10°
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
Ratio to I²R Loss for same Load Generated.

FIG. 22

is connected to the armature winding upon which bear two pairs of brushes, 4-5 and 6-7. The effect of the field $K_1$ would be to produce a direct-current electromotive force between the brushes 4 and 5. A shunt winding, 8, on the four poles of this machine, controlled by the rheostat, $R$, may be adjusted to neutralize the field $K_1$ at any predetermined output from the source, $A$, thus reducing the electromotive force between the brushes 4 and 5 to zero. These latter brushes are then short circuited. If now, a slight increase of load on the source $A$ should occur the field $K_1$ would no longer be neutralized by the shunt field winding and an electromotive force would be produced between the brushes 4-5 causing a considerable flow between these brushes. This flow produces a secondary field $K_2$ at right angles to the first and of appreciable magnitude; and this second field produces an electromotive force across the other pair of brushes 6-7, which are connected to the regulating field, $F$. In series between the brush 7 and the corresponding terminal of the field, $F$, is connected a series winding on the poles of the exciter, designed to neutralize the magnetomotive force of the current through the armature winding between the brushes 6 and 7, so that the output from these brushes will have no disturbing effect on the exciter field.

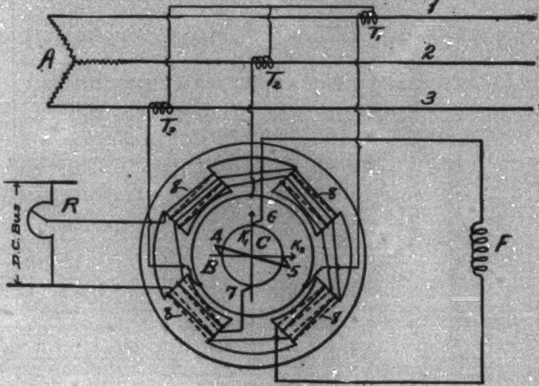

FIG. 23

This type of exciter possesses a number of important features in connection with alternating-current regulation, which may be briefly enumerated as follows:

1. It will be seen that it acts as a multiplying device by reason of the magnifying effect of the current between the short circuited brushes, and can therefore be made exceedingly sensitive to small changes in the alternating-current load.

2. It can be made to respond to any desired phase component of the alternating current by a suitable angular relation between the exciter armature and the armature of the synchronous motor which drives it. Thus for controlling the charge and discharge of a storage battery this exciter would be adjusted to respond to the energy component of the alternating current.

3. For controlling the power factor on the alternating-current circuit the two pairs of brushes 4-5 and 6-7 may be interchanged so that the latter are short-circuited while the former are connected to a field winding on any synchronous apparatus connected to the alternating-current circuit. The exciter will then be responsive to the wattless component of the alternating current and can be made to control the field of the synchronous apparatus in such a way that this apparatus will supply practically all or any desired proportion of this wattless current. For controlling both the energy fluctuations and the power-factor two such exciters may be operated, one of which is responsive to the energy component and the other to the wattless component of current.

Another advantageous feature of this exciter lies in the fact that the secondaries of the current transformers may be short-circuited at any time with the result of merely killing the regulating function. It is not necessary to disconnect the connections to the collector rings before doing this, even with considerable excitation in the shunt field winding of the exciter, since the armature reaction is so great that a short-circuit will produce only a nominal flow of current sufficient to demagnetize the fields. Similarly, in putting the apparatus into service the rheostat, *R*, if properly calibrated may be set for any desired constant load on the source, *A*, and after all the main connections are closed so that the battery is merely floating on the system, the short-circuiting switch across the secondaries of the current transformers may be opened and the load on the source, *A*, will immediately be held at the constant predetermined value for which the rheostat, *R*, has been set.

## APPENDIX

A more general solution for the wave shape of alternating electromotive force in the split-pole converter of the two section type is given below, using the nomenclature shown in Fig. 24 as follows:

$\gamma_b$ = the arc covered by the principal pole section.
$\gamma_c$ = the arc covered by the auxiliary pole section.
$2\,\delta$ = the neutral arc between pole tips.
$\rho$ = the pole section pitch.
$\theta$ = the angular distance of any point on the pole faces from the origin $A$.

$\theta' = \theta - \frac{\pi}{2n}$ = the angular distance of the same point from the secondary origin $O$.

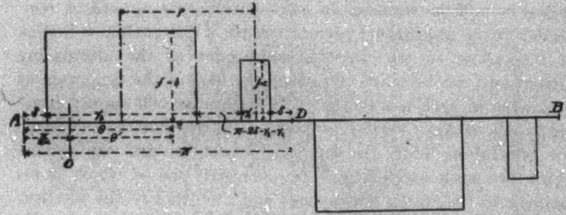

FIG. 24

$b$ = the flux density under the principal pole section.
$c$ = the flux density under the auxiliary pole section.

Repeating equation (6) we have

$$a_n = \frac{2}{n\pi}\sqrt{\left\{\int_0^{\pi} f \sin n\theta \, d(n\theta)\right\}^2 + \left\{\int_0^{\pi} f \sin n\theta' \, d(n\theta')\right\}^2} \qquad (6)$$

But the expression $\int_0^{\pi} f \sin n\theta \, d(n\theta)$, after integrating and substituting the values in Fig. 24 becomes

$$b\,[\cos n\delta - \cos n(\delta+\gamma_b)] + c\,[\cos n(\pi-\delta-\gamma_c) - \cos n(\pi-\delta)]$$
$$= b\,[\cos n\delta - \cos n(\delta+\gamma_b)] + c\,[\cos n\delta - \cos n(\delta+\gamma_c)]$$

likewise $\int_0^{\pi} f \sin n\,\theta' \, d\,(n\,\theta')$ becomes

$$b\left\{1-\cos n\left(\delta+\gamma_b-\frac{\pi}{2n}\right)\right\}+c\left\{\cos n\left(\pi-\delta-\gamma_c-\frac{\pi}{2n}\right)-\right.$$

$$\left.\cos n\left(\pi-\delta-\frac{\pi}{2n}\right)\right\}-b\left\{\cos n\left(\pi+\delta-\frac{\pi}{2n}\right)+1\right\}$$

$$=b\,[\sin n\delta-\sin n(\delta+\gamma_b)]-c\,[\sin n\delta-\sin n(\delta+\gamma_c)]$$

Substituting these values in equation (6) and making the necessary trigonometrical transformations. remembering that

$$\rho=\pi-2\,\delta-\frac{\gamma_b+\gamma_c}{2}$$

we have

$$a_n=\frac{4}{n\pi}\sqrt{b^2\sin^2\frac{n\gamma_b}{2}+c^2\sin^2\frac{n\gamma_c}{2}+2\,b\,c\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho} \tag{9}$$

this gives for the amplitude of any harmonic in equation (3)

$$\frac{8k}{\pi n^2}\sin\frac{n\beta}{2}\sqrt{b^2\sin^2\frac{n\gamma_b}{2}+c^2\sin^2\frac{n\gamma_c}{2}+2\,b\,c\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho} \tag{10}$$

and representing the ratio of any harmonic to the fundamental by $h$ we have

$$h=\frac{1}{n^2}\frac{\sin\frac{n\beta}{2}}{\sin\frac{\beta}{2}}\sqrt{\frac{b^2\sin^2\frac{n\gamma_b}{2}+c^2\sin^2\frac{n\gamma_c}{2}+2\,b\,c\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\,\rho}{b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho}} \tag{11}$$

This expression gives the relative value of any harmonic in terms of the two pole section arcs $\gamma_b$ and $\gamma_c$, the corresponding field strengths $b$ and $c$, the pole section pitch $\rho$ and the angular span of the armature section $\beta$. Equation (11) may also be written

$$h=\frac{1}{n^2}\,\frac{\sin\frac{n\beta}{2}}{\sin\frac{\beta}{2}}\sqrt{\frac{\sin^2\frac{n\gamma_b}{2}+\frac{c^2}{b^2}\sin^2\frac{n\gamma_c}{2}+\frac{2\,c}{b}\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho}{\sin^2\frac{\gamma_b}{2}+\frac{c^2}{b^2}\sin^2\frac{\gamma_c}{2}+\frac{2c}{b}\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho}} \tag{12}$$

in which the ratio of the harmonic to the fundamental is expressed in terms of the ratio between the field strength of the auxiliary section and that of the principal section.

Let $b = b_0$ when $c = 0$, also let the amplitude of the fundamental electromotive force be kept constant by slightly varying the value of $b$ as $c$ is varied. Then from equation (9) we have

$$b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho = b_0^2\sin^2\frac{\gamma_b}{2} \tag{13}$$

Substituting this in equation (11) we have

$$h=\frac{1}{n^2}\cdot\frac{\sin\frac{n\beta}{2}}{\sin\frac{\beta}{2}}\cdot\frac{\sqrt{\frac{b^2}{b_0^2}\sin^2\frac{n\gamma_b}{2}+\frac{c^2}{b_0^2}\sin^2\frac{n\gamma_c}{2}+\frac{2bc}{b^2_0}\sin\frac{n\gamma_b}{2}\sin\frac{n\gamma_c}{2}\cos n\rho}}{\sin\frac{\gamma_b}{2}} \tag{14}$$

For any assumed value of $c/b_0$ the value of $b/b_0$ may be determined from equation (13) and these two in (14) will give the corresponding value of $h$.

The direct current voltage $V$ will be (see equation 2)

$$V = k\int_0^\pi f\,d\,\theta$$

and using the nomenclature in Fig. 24, this becomes

$$V = k\,\{b\,\gamma_b+c\,\gamma_c\} \tag{15}$$

From (10) the mean effective value of the fundamental is

$$E=\frac{4\,k\sqrt{2}}{\pi}\sin\frac{\beta}{2}\sqrt{b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2\,b\,c\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos\rho} \tag{16}$$

and the ratio of alternating- to direct-current voltage

$$\frac{E}{V}=\frac{4\sqrt{2}}{\pi(b\gamma_b+c\gamma_c)}\sin\frac{\beta}{2}\sqrt{b^2\sin^2\frac{\gamma_b}{2}+c^2\sin^2\frac{\gamma_c}{2}+2bc\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos} \qquad (17)$$

or

$$\frac{E}{V}=\frac{4\sqrt{2}}{\pi\left(\gamma_b+\frac{c}{b}\gamma_c\right)}\sin\frac{\beta}{2}\sqrt{\sin^2\frac{\gamma_b}{2}+\frac{c^2}{b^2}\sin^2\frac{\gamma_c}{2}+2\frac{c}{b}\sin\frac{\gamma_b}{2}\sin\frac{\gamma_c}{2}\cos} \qquad (18)$$

which gives this ratio in terms of the ratio $c/b$

If $c = o$, (17) becomes

$$\frac{E_0}{V_0}=\frac{4\sqrt{2}}{\pi\gamma_b}\sin\frac{\beta}{2}\sin\frac{\gamma_b}{2} \qquad (19)$$

If the amplitude of the fundamental is held constant, we have $E = E_0$ and by substituting (13) and (19) in equation (17)

$$V = V_0\left\{\frac{b}{b_0}+\frac{c}{b_0}\cdot\frac{\gamma_c}{\gamma_b}\right\} \qquad (20)$$

From equations (13) and (20) the variation of the direct-current electromotive force may be derived for any change in the auxiliary field strength, on the assumption that the alternating-current electromotive force is held constant by varying the strength of the principal pole section. If the converter is connected to a source of constant alternating electromotive force, this variation in the field strength of the principal pole section, if not obtained by manual adjustment, will be brought about by the magnetizing effect of the wattless currents in the armature winding.

From equations (13), (14), and (20), the curves shown in Fig. 19 were obtained.

In Fig. 25 curves have been plotted giving the variation in field strength of the main and auxiliary poles for various direct-current voltages, the amplitude of the fundamental wave of alternating electromotive force being held constant, these curves being plotted from equations (13) and (20), the following values (corresponding to the design of a machine actually built) being assumed for the pole face arcs:

$$\gamma_b = 104°$$
$$\gamma_c = 44°$$
$$\rho = 74°$$

It will be noted that a certain maximum direct-current voltage is reached which cannot be exceeded under the condition of constant alternating electromotive force, since the reduction in the main field strength necessary to maintain this latter condition more than offsets the further increase in the auxiliary field strength. It will also be noted that over a wide range of variation of the direct-current voltage the main field strength remains nearly constant, passing through a maximum point

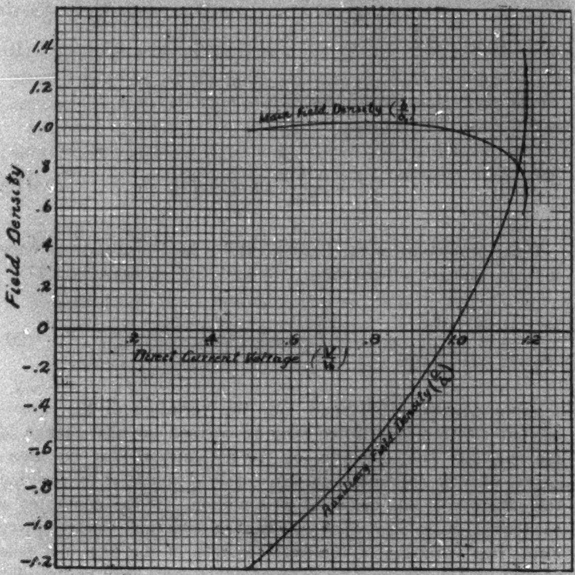

FIG. 25

from which it recedes as the direct-current voltage is increased or diminished.

By reference to equation (12) it will be seen that certain of the harmonics may be eliminated by giving suitable values to $\gamma_b$ and $\gamma_c$. For example, if $\gamma_b = \frac{4\pi}{7}$ and $\gamma_c = \frac{2\pi}{7}$, the 7th harmonic will disappear. These values for the pole section arcs leave but very little neutral area for commutation, even if the pole sections are contiguous, and call for an auxiliary pole section arc one-half that of the principal pole section, while the angle $\rho$ is $\frac{3\pi}{7}$, necessitating control of both pole sections in order to maintain unity power factor (unless the mean value of $c$ is negative, which will reduce the kw. output). The 5th harmonic cannot be entirely eliminated in this way, and the higher harmonics are not of sufficient importance to warrant a design which is otherwise disadvantageous.

Some of the higher harmonics may also be suppressed by using a fractional pitch winding. This method however cannot be carried far enough to have an appreciable effect on the value of harmonics below the 9th.

## DISCUSSION ON "VOLTAGE RATIO IN SYNCHRONOUS CONVERTERS, WITH SPECIAL REFERENCE TO THE SPLIT-POLE CONVERTER" AND ON "APPLICATION OF STORAGE-BATTERIES TO REGULATION OF ALTERNATING-CURRENT SYSTEMS." ATLANTIC CITY, N. J., JULY 1, 1908.

**P. M. Lincoln:** These papers give a much clearer insight into the theory and expected performance of the so-called "split-pole" synchronous converter than anything which has been produced up to date. With these papers before him, the engineer who contemplates using this type of machine is in much better position to judge of its merits than ever before.

In both papers, almost the only question discussed, so far as the split-pole synchronous converter is concerned, is that of wave form. Although of prime importance, this question of wave form is by no means the only one which is to determine whether this type of construction will stand the test of time, or whether, on the other hand, it will find its way into the oblivion of the monocyclic system, and other disappointed hopes. This split-pole method of obtaining a variable voltage must be compared with other methods of obtaining the same results, not only with respect to wave form, but also with respect to relative capacity, cost, efficiency, commutation, power-factor, weight, floor space, heating, reliability, noise, possibility of resonance, rapidity of voltage change, liability of hunting, etc. It is only the test of time that can prove out this machine. Some light, however, can be thrown on the matter by further discussion of some of the questions mentioned above.

*Wave form.* In my discussion of this machine before the Institute in February, the following statement occurs:

> With a field form other than a sine, the wave form across the electrical diameter deviates from sine form less than that across any chord.

While this statement is perfectly true for the general case, I wish to take this opportunity to acknowledge that it does not apply to the case of the synchronous converter as ordinarily constructed. As Professor Adams has pointed out, harmonics of any one order can be eliminated from the electromotive-force wave of a synchronous converter by suitably choosing the angle between adjacent taps. For instance, in a converter in which the adjacent taps are spaced at an angle of $\frac{2\pi}{3}$, or 120 deg., third harmonics will be eliminated. With adjacent taps spaced at an angle of $\frac{2\pi}{5}$, or 72 deg., fifth harmonics will be eliminated. With taps $\frac{2\pi}{7}$, or 51.4 deg. apart, seventh harmonics will be eliminated, etc.

In the above not only are the third, fifth and seventh harmonics eliminated from the electromotive-force wave, but also in each case multiples of these harmonics are eliminated. Likewise, with taps spaced apart by an angle of $\frac{2\pi}{2}$, or 180 deg., all second harmonics are eliminated and multiples thereof; in other words, all even harmonics. With taps $\frac{2\pi}{4}$, or 90 deg. apart all fourth harmonics and multiples thereof are eliminated, etc. Professor Adams has pointed out that in general, harmonics enter into a wave form in values in inverse proportion to their order; that is, ordinarily the third harmonic will be of greater value than the fifth, the fifth of greater value than the seventh, etc.

In the most general case, that is, where even harmonics enter as well as odd, the same relation will hold. In general, the second harmonic will be of greater value than the third, the third greater than the fourth, etc. It follows, therefore, that in this general case the 180-deg. taps give rise to a wave form which deviates from a sine to the minimum extent, since it eliminates all even harmonics.

It must be borne in mind, however, that so long as the negative and positive fluxes in a synchronous converter, or other electrical machine, are of the same shape, even harmonics are eliminated owing to this fact. We can, therefore, entirely neglect the matter of even harmonics in selecting angular distance between taps in synchronous converters, and can make the selection such that the maximum of odd harmonics will disappear. From the above it is evident that the connection which will eliminate third harmonics and multiples thereof will give rise to the wave form which deviates the least from the sine wave. It is evident, therefore, that in a synchronous converter or other electrical machine in which the positive and negative field forms are of the same shape, the 120-degree taps, not the 180-degree, will give a wave form which deviates a minimum amount from a sine.

In a split-pole synchronous converter, therefore, the secret of obtaining a variable voltage by variation of the field form, and at the same time a wave form fairly free from harmonics, is: first, to use a three-phase converter; second to design the field form so that it is composed as far as possible of nothing but a fundamental form upon which is superposed a variable third-harmonic form. It is evident that a constancy of wave form can be realized in a three-phase synchronous converter only as we approach the condition that the superposed variable-field form contains nothing but third harmonics or multiples thereof. Further consideration will show that in the three-part pole converter it is not difficult to obtain a close approximation to this condition.

This fact is quite readily shown by an inspection of Figs 9, 11 and 13 of Mr. Woodbridge's paper. An inspection of these figures shows that by far the larger part of the field distortion takes the form of a superposed third harmonic. In Fig. 9 this superposed third is about 33 per cent. of the maximum field value, in Fig. 11 about 54 per cent., and in Fig. 13 the third is practically absent. During this field variation the total voltage variation is about 19 per cent., thus proving out in a beautiful manner the theoretical curve shown by Professor Adams in Fig. 6. Since these third harmonic variations in the field form do not affect the 120-degree electromotive-force wave, comparatively slight changes in the resulting wave form may be expected, as shown by Figs. 10, 12 and 14.

With a two-part pole the problem of eliminating the higher harmonics is not so simple. Refer, for instance, to Fig. 7, of Professor Adams's paper. The typical two-part field form shown therein gives a rather large third, but inspection also shows that with such a two-part field form it is impossible to confine the variations to thirds exclusively, as is the case in the three-part pole machine. In order to have practically nothing but the third harmonic enter, it would be necessary to have a downward projecting lobe on the left-hand side of this field form as well as on the right-hand side as shown. Since it is impossible to confine the field-form variations to thirds, it follows that the wave-form variations will be much greater in the two-part pole synchronous converter than in the three-part.

Mr. Woodbridge suggests an ingenious scheme in Fig. 18, for further reducing the effects of the fifth and seventh harmonics in the case of a two-part pole synchronous converter. He, however, suggests a rather serious objection to the scheme, in noting that the loss in a single bar of a converter so connected is 50 per cent. higher than the average loss. That the average per slot is not so high will assist matters inside the slot, but it is well known that heavily loaded windings suffer from heating at points outside, not inside the slots. This objection becomes still more important when we consider that the single-bar loss becomes still more than 50 per cent. above the average with power-factors other than 100 per cent.

I might note, in passing, that in order to arrive at the true electromotive-force curves both Figs. 20 and 21 of Mr. Woodbridge's paper should have a large third harmonic added, the values of which should be nearly 20 per cent. in Fig. 20 and nearly 10 per cent. in Fig. 21. While these third harmonics do not appear in the external three-phase circuit, they do cause transformers placed across the diameter (Fig. 20) and the 82 per cent. chord (Fig. 21) to pass through a magnetizing cycle which will increase their iron losses in the approximate ratio of the entering third; that is, 20 per cent. increase for Fig. 20 and 10 per cent. increase for Fig. 21.

A class of service from which this type of synchronous converter is effectually barred is the Edison three-wire circuits in which the neutral is brought out from the transformers and connected to the neutral of the lighting system; as any attempt to use the machine in this service would superpose the third harmonic upon the direct-current circuits, and also cause circulating currents in the transformer windings, if more than one transformer were tapped into the neutral.

In general, so far as wave form is concerned, it seems possible so to design the three-part synchronous converter pole that no appreciable circulating current will be caused in the outside circuits on account of wave-form variation, provided three-phase converters are used. In the case of the two-part pole, the circulating currents caused by variable wave form will probably be appreciable, but not disastrous, unless very large alternating and direct-current voltage variations be attempted.

*Capacities and costs.* In order to obtain the variable voltage feature of the split-pole converter, it is necessary to make a considerable sacrifice in the output that can be obtained from a given amount of material. This can best be shown by reference to Figs. 11 and 13 of Mr. Woodbridge's paper. Fig. 11, for instance, shows the resulting field form of one of these split-pole converters when it is delivering its maximum voltage. The deep notch out of the middle of the field form in Fig. 11 as measured by a planimeter amounts to about 33 per cent. of the area under the curve. In other words, if the notch were absent and the converter armature winding suitably changed, an increase in capacity could be obtained from the same converter of some 25 per cent. without increasing the cost of the rotary over one designed with a field form like Fig. 11. This means that a sacrifice of 33 per cent. in capacity must be made in order to obtain the variable voltage feature. Coupled with its other disadvantages, this is probably enough to eliminate the three-part-pole converter from any active competition with other modes of obtaining variable voltage.

Referring to Fig. 13, the same criticism applies, although in this case it is not of so much importance, as this Fig. shows the minimum voltage condition and not the maximum voltage as indicated in Fig. 11. The converter with a field form as in Fig. 13 suffers a loss in capacity of about 25 per cent. as compared with a converter of normal field form, the material of the teeth therein being worked to the same magnetic density in both cases.

Referring to the two-part pole scheme, the same criticism applies, but the capacities do not suffer quite so large a decrease. For instance, the arrangement shown by Mr. Woodbridge in Fig. 17 shows a notch between the main and auxiliary poles of 20 per cent of the available pole width. This would have the effect of decreasing the capacity of such a machine in approximately the same ratio. Another criticism of the arrangement shown in Fig. 17 is that the notch in which the brushes rest is given a width of only 30 degrees or 16⅔ per cent. of the pitch. Experience indicates that this is too narrow for good commutating conditions. A width of 20 to 25 per cent should be allowed for the inter-polar space even in a converter of normal design, and this split-pole type should have a still wider neutral. Taking this into consideration, a still further decrease in capacity will result unless the designer is willing to take considerable risk with the commutation.

While it is probable that Mr. Woodbridge's suggested pole arrangement of Fig. 17 can be considerably bettered so far as capacity is concerned, the output that can be obtained from a given amount of material will always be much less in a split-pole converter than in one of normal design. The cost of obtaining a given voltage variation by this means is at best probably as great or greater than that of obtaining the same effect in other ways.

*Efficiency and heating.* In addition to the split-pole converter requiring considerably more active iron in its armature, this iron is carried through a flux cycle which introduces much greater losses than in the case of a converter of normal design. For instance, in Fig. 11, of Mr. Woodbridge's paper, the introduction of the notch in the field form not only increases the amount of iron in the teeth by about 33 per cent. but also increases the losses that take place in this iron by about 15 per cent. The total iron losses including the body of the armature as well as the teeth at the maximum voltage are increased by about 35 per cent. to 50 per cent. over those of a normal design.

With a two-part pole design as shown in Fig. 17, of Mr. Woodbridge's paper, the iron losses will be increased about 15 per cent. at maximum voltage and about 35 per cent. at minimum voltage. This coupled with the fact that this design requires about 20 per cent. additional material increases the total iron losses in such a machine from 40 per cent. to 60 per cent. The field copper losses will be increased on account of the doubled or trebled number of fields to be magnetized. Armature copper loss will be increased, first, because the machine will be larger and, second, because of the circulation of the higher harmonic currents.

It is evident that the best efficiencies that can be obtained from such a machine will be as low, and probably lower than the alternative method of obtaining voltage variation—by means of a separate synchronous booster mounted on the same shaft as a normally designed converter.

*Commutation.* So far as commutation is concerned, the design of the three-part pole machine should not introduce any particular difficulties or problems, provided the notch between the poles is not made too small. The field strengths adjacent to the brushes, although variable, are always equal and opposite, so that the point at which commutation takes place is not subjected to a variable field. This cannot be said of the two-part pole machine. Refer to Fig. 17, for instance, of Mr. Woodbridge's paper, and note that the brushes are set at points *A* and *D*. The small field M. P. is assumed to vary from a magnitude equal to field G. H. in the positive direction to the same magnitude in the negative direction. As this variation occurs it is very evident that the field strength at the points *A* and *D* must vary, since at the one extreme the adjacent fields are equal and opposite, and at the other, equal and the same. If, therefore, proper commutating conditions are secured at one extreme, it will be necessary to sacrifice commutating conditions at the other extreme. It is true that the field at the point of commutation can be made to act in a direction to assist commutation. But it is impossible to take advantage of this feature, since in this case we would have a condition very similar to that of a commutating-pole generator the strength of whose commutating pole varies from full value to zero, depending upon conditions totally independent of the current to be commutated. It is evident that under these conditions the field at the commutating point is a hindrance, not a help, to commutation.

*Resonance.* In long-distance transmission systems, or systems wherein considerable amounts of high-tension cable are used, there is of course, always a considerable amount of capacity. This capacity, coupled with the reactance of transformers presents the possibility of resonance being set up therein. Although the three-phase connection of a split-pole converter eliminates the third harmonic and all multiples thereof, Professor Adams has shown that all other harmonics appear in the system to exactly the same extent in the 120-degree electromotive-force wave as in the 180-degree wave.

It is evident, therefore, that such a machine, even connected three-phase, will impress harmonics upon the outside circuits, which will vary both in order and in magnitude. That at some point in the voltage range a condition of resonance will occur is certainly not without the bounds of possibility. This is particularly true with the two-part-pole converter, since, as pointed out above, it is impossible with this type to eliminate the higher harmonics.

*Noise.* Not all of the causes for noisy electrical machines are known. Some of them, however, have been determined and one of the most important is the sudden transition of armature teeth from one magnetic density to another. The fact that a relatively small number of armature teeth are at a given magnetic density at once is another contributing cause. Evidently both of these causes enter to make the designing of a noiseless split-pole converter difficult, whether it be of the three-part- or the two-part-pole type. In order to obtain a design to give noiseless operation, it may often be necessary to make a considerable additional sacrifice in capacity.

*Rapidity of voltage change.* In the application of storage batteries to what Mr. Woodbridge calls the "regulation" of alternating-current systems; or, in other words, to assuming load fluctuations that would otherwise fall on the generating plant, ability to change the voltage of a rotary rapidly is highly essential, since rapidity in voltage change means rapidity on the part of the storage battery in assuming the fluctuations of load.

In order to change the voltage of either a split-pole converter or a normal converter equipped with a separate synchronous booster (similar to Fig. 5, Mr. Woodbridge's paper) it is necessary to cause a certain amount of change in the field flux, in the first case of the main converter poles, and in the second case of the booster poles. Professor Adams has pointed out that the amount of field flux necessary to produce a given voltage change in the split-pole machine is approximately in proportion to the harmonic introduced into the converter in order to produce that voltage change. Thus the total flux change necessary to produce a given voltage change is three times greater when that voltage change is caused by superposing a third harmonic than if caused by changing the fundamental, five times greater if caused by a fifth harmonic, etc. The creation, or the changing, of location of magnetic fluxes requires energy in proportion to the volume of flux created or changed. With a given force acting to produce flux changes it is evident, therefore, that the rapidity of voltage change is at least three times greater when acting upon the fundamental frequency (as is the case in a converter with synchronous booster) than when acting through the agency of a third or higher harmonic (as is the case with the split-pole converter). In this particular, therefore, the split-pole converter is at considerable disadvantage when compared with the alternative of a normal converter equipped with a synchronous booster.

Another important advantage accruing to the separate booster arrangement in point of rapidity of voltage change, is that the flux upon which the regulator must operate in order to change the voltage of the booster field may be left unhampered with dampers. In order to insure proper operation, the main rotary fields, no matter whether split pole or otherwise, should be equipped with relatively heavy dampers.

In the case of the split-pole machine the regulator, of whatever kind, must cause magnetic fluxes to change their positions and magnitudes in spite of the enveloping damper. In the separate booster machine the omission of dampers from the booster fields, while it does not interfere with the running characteristics, gives the regulator an opportunity of operating upon a magnetic flux not enveloped by a damper, and this gives a much higher rapidity of action. Just how much this point will affect the relative speed of voltage changes is problematical, but it is probable that this effect will be still greater than the one mentioned in the preceding paragraph, thus placing the separate booster machine in an entirely different class so far as the rapidity of voltage change is concerned.

It is on this score of rapidity of action that Mr. Woodbridge bases an argument for the converter as against the motor-generator. He points out that in the motor-generator set there is a lag between the time when the battery begins to discharge the direct-current machine and the time when this energy begins to appear in the alternating-current circuit, owing to the fact that the "lost motion", so to speak, in the motor-generator set must be taken up. While this time lag is theoretically present, it hardly deserves the term "appreciable" applied to it by Mr. Woodbridge. I have considered a number of typical motor-generator sets and find that the time lag mentioned by Mr. Woodbridge is of the order of 0.001 seconds. Compared to the time required by mechanical movement on the part of a regulator and the time required for field flux changes, the above time lag is zero. I agree with Mr. Woodbridge's conclusion that a converter is preferable to a motor-generator for the purpose described, but my conclusion is not arrived at by the same process of reasoning.

In conclusion, it is my opinion, for reasons set forth above, that the split-pole converter has disadvantages that far outweigh its advantages, when compared with the alternate, a normally developed converter with a synchronous booster of the same number of poles, mounted on the same shaft.

**A. S. Hubbard:** The paper by Mr. Woodbridge is interesting as outlining some of the methods for compelling and controlling storage-battery charge and discharge to steady the load on alternating-current generators. These methods must necessarily be mainly suggested and prospective, because so far as I am informed, there have been installed in this country but five storage-battery plants for the regulation of alternating-current loads. One of these five plants, however, is not now in operation as an alternating-current regulating plant, but was installed for the purpose of controlling the output from two generators at different voltages, tied together and to the transmission lines by transformers. Two current coils, each taking current from one of the generators, actuated a single carbon regulator which controlled a direct-current booster in the battery circuit. The regulation of this plant was very erratic, being only within about 33 per cent.; that is, the load on the generators varies from 33 per cent. above to 33 per cent. below the average.

The single-phase plant mentioned by Mr. Woodbridge, although included in the five, cannot be taken as a fair example of alternating-current load regulation, except for isolated, special cases, such as the plant of the Spokane and Inland Railway, where frequency or phase-changing is necessary. The regulation of this plant is effected by a single coil regulator actuated by current variations. As this coil is installed in the circuit leading to the induction motor, its current will be proportional to the current supplied to the motor, which current is affected by the line voltage, load, and frequency. Though I believe this plant to be successful, owing to peculiar local conditions, I think Mr. Woodbridge will agree that in general, definite, close regulation cannot be obtained with current regulation, except where there are no power-factor changes, or where the power-factor changes with load in a definite way; that is to say, that successful current regulation has been and will be the exception rather than the rule. That certainly is the conclusion I came to after considerable experimenting, as a result of which I devised and put in operation regulation by current times power-factor in a plant where regulation by current alone had been a failure.

The third plant includes a two coil regulator, of the dynamometer type. With this type of regulator the battery may be compelled to charge and discharge in response to variations of the true energy; that is, account can be taken of current, voltage, and power-factor variations. I have no information as to the completion of this plant, but the regulation obtained some months ago was but 25 per cent; that is, the watt load varied from 25 per cent below to 25 per cent above the average, with considerably smaller charges and discharges than the size of battery would seem to warrant. As a carbon regulator with the usual retarding spring is used at this plant the lower the average load the worse the regulation.

The fourth plant has been in operation continuously for something over two years, except for slight delays due to the grounding of the series transformers on two occasions by lightning. Water power is here used to generate 13,200-volt, three-phase, 25-cycle alternating current. This is all transmitted approximately five miles to a sub-station, where a portion of the power is transformed and converted and used for direct-current railway work and alternating-current lighting. The rest of the power is used at other sub-stations, one being located 12 miles away. The common sub-station contains two converters, 150 kw. each, a frequency changer, and a 280-cell, 400-ampere, one-hour battery, with its booster and regulating apparatus. The regulation at this plant is in accordance with variations of amperes times power-factor and is accomplished as follows:

In the incoming high-tension lines, three current transformers are installed, with their secondaries connected to a second set of three current transformers located back of the switchboard and provided with sectional secondaries connected to a compensator head. From the compensator head, the current is led to the collector rings of the rectifier. The rectifier consists of a number of discs of armature steel perforated near their edges and mounted on a shaft. A bipolar winding is threaded through the holes and connected at one end at points 120 degrees apart to the collector rings and at the other end to a commutator. The rectifier is connected to and driven by a bipolar synchronous motor built with special reference to minimum hunting.

The alternating currents from the series transformers produce a rotary field in the rectifier, which latter is mechanically rotated at the same speed, but in the opposite direction, by the synchronous motor. As the synchronous motor armature turns in synchronism with the voltage of the system, and the rotary field in synchronism with the current, there is produced in space a field whose position is stationary so long as the power-factor remains unchanged. A change in current without a change in power-factor merely increases the magnitude of the field, but does not change its position.

A single pair of brushes, *a*, arranged diametrically opposite and bearing on the commutator at points of maximum voltage, when the power generated is at 100 per cent power-factor, will give a direct current which will vary in accordance with variations of the alternating current transmitted, independent of change of power-factor within very wide limits, because the current transformers feeding the rectifier tend to preserve their current transformation ratio irrespective of changes in resistance of their secondary circuits. And while the position of the field changes, the voltage on the commutator of the rectifier also changes and rises until of sufficient value to deliver a direct current over the circuit connecting the *a* brushes, equal to the transformation ratio value of the current transformers. When, however, as is the case at the plant in question, a second set of brushes, *b*, is used on the commutator at 90 electrical degrees from the others and connected to a circuit having resistance and inductance characteristics corresponding to the characteristics of the circuit connected to the other brushes, a by-pass is provided and two direct currents are obtained, one of which, $a'$, varies as the energy current component and the other, $b'$ as the wattless current component of the current in the alternating current line. $a'$ is used to regulate the battery charge and discharge, and $b'$ can be used to correct the power-factor by changing the excitation of a synchronous motor or a synchronous converter. The direction of $b'$ is in one direction for lead and in the other direction for lag. The watt regulation at this plant is 3.5 per cent; that is, the kilowatt load on the generators varies only 3.5 per cent from any average.

The load regulation is so good that the voltage is constant, and the Tirrell regulator formerly used at the power house has been taken out and used on the lighting circuit supplied from the induction-motor-driven frequency-changer. The 3.5 per cent regulation is obtained with battery charges up to the one hour rate and with discharges of two and one half times the one-hour rate and with booster voltages up to 140 volts.

The sectional series transformers and the compensator head are provided to enable the energy load to be changed at will, during operation, from about 50 kw. to 1000 kw. The regulation is 3.5 per cent. of any value between these limits.

Safety devices are provided so that if the synchronous motor goes out of step, or a short-circuit comes on the lines, the series transformers are automatically short-circuited and the regulation "killed."

It will be noted that variations of output from this rectifier do not affect the load on the synchronous motor driving it, nor has the rectifier any motor action, both very important points.

The fifth plant is a 60-cycle, 2300-volt, three-phase system, a turbine being used ordinarily for the generation of power. The regulating equipment of this plant is of the same type as that previously described, except that the apparatus is designed for 60 cycles. The rectifier and its synchronous motor have six poles, and but one series transformer is used in one phase. The regulation obtained here is 4 per cent of any average, the usual average being 800 kw. The variation is but 32 kw. In this plant also, the load is kept so steady that it is not necessary to operate the Tirrell regulator for voltage regulation, even though a portion of the output is used for lighting. This plant has been in operation for about six months.

While the multiplying features mentioned by Mr. Woodbridge are present in the rectifiers of the fourth and fifth plants here described, as well as in that described by him, this multiplication is not due so much to any shift of field or current in the by-pass circuit as it is to an inherent characteristic of the rectifier fed by series transformers, and can be made of any desired value within wide limits by proper design. The direct-current output from these rectifiers is about 40 watts (10 volts and 4 amperes) the direct current from the *a* brushes varying from about 2.75 amperes to about 5.5 amperes for an energy change on the line of only 3.5 per cent plus or minus. By changing the relation between the characteristics of the *a* and *b* circuits, various effects and any desired combination of currents and of energy regulation can be obtained. But one of these rectifiers is required for both load regulation and power-factor correction, the *a* circuit controlling the load regulation, and the *b* circuit the power-factor.

The dynamometer control is an electromechanical device that has no pronounced inertia; in my opinion it is not so good as the rectifier control of plants, with water wheels, steam turbines, or gas engines as prime movers.

The question as to what type of apparatus to use for the connecting link for the transfer of energy between the alternating-current and the direct-current circuits, is one in which enters the efficiency of the apparatus and the magnitude and direction of the loads to be transferred. If an alternating-current booster is used, in most cases this belongs to the high-tension side.

The split-pole converter is undoubtedly a distinct contribution to alternating-current distribution, although the changing shape of the voltage wave of this machine as its alternating-current direct-current ratio is changed, may seriously affect the operation of the small synchronous motor proposed for driving the rectifier at the Gary plant. My experience is, that to insure stability and absence of hunting in a synchronous motor, the wave shape of this motor must correspond to the wave shape of the nearest preponderating synchronous machine.

**W. L. Waters:** Messrs. Adams and Woodbridge have worked out in an interesting way the mathematical theory of the split-pole converter. In working out any such problem mathematically it is necessary to make a number of assumptions in order to simplify the problem. Both Messrs. Adams and Woodbridge show that it is mathematically possible by means of a split-pole converter to obtain a considerable voltage variation without introducing serious distortion of wave form, or any great number of higher harmonics into the wave form of the converter. It is then simply a question as to whether these mathematical deductions are borne out in practice.

The statement that any particular harmonic can be entirely eliminated by suitably choosing the angle between the various taps on the armature and the pitch of the winding may be mathematically correct, but I doubt very much whether this will be found true in practice. The fact that the poles are not all exactly equal, and that consequently there are local circulating currents in any multiple-circuit converter armature is neglected; as is also the fact that there is a certain amount of electrostatic capacity between different parts of the armature winding and the frame, which causes local higher harmonics circulating currents and a tendency for the higher harmonics to reappear in the voltage wave form. There are a number of similar assumptions that are necessarily made in any mathematical treatment, but the extent to which they will modify the wave form obtained under actual operating conditions and under the special conditions which at times occur in an operating power circuit, is a matter of actual experience.

Mr. Lincoln has cited a number of features in which this split-pole is inferior to the standard converter: its increased size; increased core loss; increased field copper loss; increased armature heating, due to the fact that the alternating and direct currents do not properly neutralize each other with the varying voltage ratio; and also that on such a converter provided with dampers the voltage control will be extremely slow-acting compared with the standard alternating- or direct-current booster. I think, however, that Mr. Lincoln has not sufficiently emphasized the comparatively poor commutation of these converters under general operating conditions of the power circuit.

If there is any disturbance on the system causing hunting and sudden change in voltage or speed of the converter, there will be local equalizing currents flowing through the armature conductors, and the rotating field of the armature will fluctuate rapidly both in magnitude and in position. Similar fluctuating fields will be induced by currents in the dampers in the pole-faces, with the result that the distribution of magnetism on the pole-face will fluctuate and in consequence the voltage ratio and the terminal voltage will fluctuate. This will make the loads on the converter and its voltage and current fluctuate, and will greatly increase the tendency of the machine to hunt. If the converter is running in parallel with a battery, this fluctuation in voltage will probably be disastrous. It is also practically certain that unless such a converter is designed with extremely large interpolar gap and neutral point (thus necessitating a large machine) it will be very much more sensitive in regard to commutation than the standard converter, this sensitiveness being due to the inequalities in the distribution of magnetism at the pole-tips and to the fact that this distribution varies from time to time.

It is not easy to see the advantages to be gained by the adoption of this split-pole converter over a standard alternating- or direct-current booster. Such a booster combination is much more flexible, quicker in acting, and introduces no distortion or circulating currents into the system. The most that can be said for the split-pole converter is that it may possibly prove a little cheaper in certain cases, but to offset this there is the introduction of higher harmonics into the system and the probability of commutation troubles and greater liabilities of hunting. The split-pole converter at the present time can only be considered as a theoretical proposition. The fact that it operates well on the test floor and performs satisfactorily under favorable conditions cannot be taken as indicating its suitability for general work. Before it is finally accepted, we must have the experience of two or three years in practical operation on a power system, subject to all the sudden variations and fluctuations that take place in such a system.

**Charles P. Steinmetz:** The synchronous converter has been with us now in commercial use for 15 years, and has always been considered as a machine giving a constant ratio of conversion. It is very remarkable, then, that in the last few years we should have found out that this ratio can be varied over a wide range. To some extent it is rather discouraging to the engineer to find in such a well-known machine a feature which he never thought of before. At the same time it is encouraging to think that even in such familiar apparatus there may be a good many latent valuable properties.

Though I have nothing to add to the subject-matter of the two papers, I would like to explain the method of operation in a slightly different manner, to show, without the use of mathematics, how the converter operates in giving a variable ratio, and thereby incidentally, I believe, also explain some misconceptions in Mr. Lincoln's criticism regarding commutation, output, and heating.

In a synchronous converter, with a sine wave of alternating voltage, and the commutator brushes set at the magnetic neutral; that is, at right angles to the resultant magnetic flux, the direct voltage is constant at constant impressed alternating voltage. It equals the maximum value of the alternating voltage between two diametrically opposite points of the commutator, or "diametrical voltage", and the diametrical voltage is twice the voltage between alternating lead and neutral, or star voltage of the polyphase system.

A change of the direct voltage at constant impressed alternating voltage can be produced:

1. Either by changing the position angle between the commutator brushes and the resultant magnetic flux, so that the direct voltage between the brushes is not the maximum diametrical alternating voltage, but only a part thereof;

2. Or by changing the maximum diametrical alternating voltage at constant effective impressed voltage, by wave shape distortion by the superposition of higher harmonics.

In the former case, only a reduction of the direct voltage below the normal value can be produced; in the latter case, an increase as well as a reduction can be produced. An increase can be produced if the higher harmonics are in phase; and a reduction, if the higher harmonics are in opposition to the fundamental wave of the diametrical or star voltage.

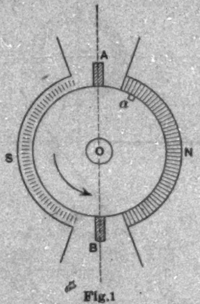

Fig. 1

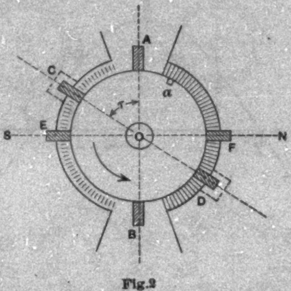

Fig. 2

A. *Variable ratio by a change of the position angle between commutator brushes and resultant magnetic flux.* In the commutating machine shown diametrically in Fig. 1, let the potential difference, or alternating voltage, between one point $a$ of the armature winding and the neutral 0; that is, the star voltage, or half the diametrical voltage, be represented by the sine wave, Fig. 3. This potential difference is a maximum, $e$, when $a$ stands at the magnetic neutral, at $A$ or $B$.

If, therefore, the brushes are located at the magnetic neutral, $A$ or $B$, the voltage between the brushes is the potential difference between $A$ and $B$, or twice the maximum star voltage, $2e$, as indicated in Fig. 3. If now the brushes are shifted by an angle $\tau$, to position $C$ and $D$, Fig. 2, the direct voltage between the brushes is the potential difference between $C$ and $D$, or $2e$

cos $\tau$ with a sine wave. Thus, by shifting the brushes from the position *A*, *B*, at right angles with the magnetic flux, to the position *E*, *F*, in line with the magnetic flux, any direct voltage between $2e$ and *O* can be produced with the same wave of alternating voltage *a*.

As seen, this variation of direct voltage between its maximum value and zero, at constant impressed alternating voltage, is independent of the wave shape, and can, therefore, be produced whether the alternating voltage is a sine wave or any other wave.

Instead of shifting the brushes on the commutator, with fixed position of the commutator brushes, the magnetic field poles may be shifted in the opposite direction, by the same angle, as shown in Fig. 4, *A*, *B*, *C*.

Instead of mechanically shifting the field poles, they can be shifted electrically, by having each field pole consist of a number of sections, and successively reversing the polarity of these sections, as shown in Fig. 5, *A*, *B*, *C*, *D*.

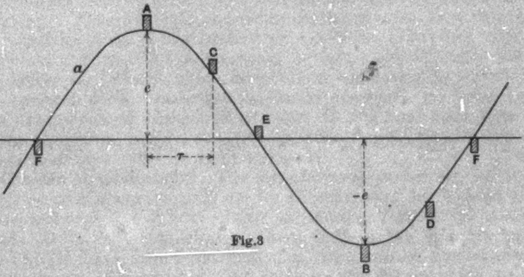

Fig.3

Instead of a large number of field-pole sections, two sections are obviously sufficient, and the same gradual change can be brought about, by not merely reversing the sections, but by reducing the excitation to zero and bringing it up again in the opposite direction as shown in Fig. 6, *A*, *B*, *C*, *D*, *E*. In this case, when reducing one section the other section must be increased by approximately the same amount to maintain the same alternating voltage.

In changing the direct voltage by mechanically shifting the brushes past the field poles, as soon as the brushes come under the field-pole faces self-inductive sparking on the commutator results, if the iron of the field poles is not kept away from the brush position by having a slot in the field poles, as indicated in the dotted line in Fig. 2, and Fig. 4*B*. With the arrangement in Figs. 2 and 4, this is not feasible mechanically, and these arrangements are therefore unsuitable. It is feasible, however, in the arrangements shown in Figs. 5 and 6; that is, when shifting the resultant magnetic flux electrically, to leave a commutating space between the polar projections of the field at the brushes, as shown in Fig. 6, and thus obtain as good commutation as in any other commutating machine.

Such a variable-ratio converter, then, comprises an armature with the brushes in fixed position, and field poles separated by interpolar spaces of such width as required for commutation. Each field pole consists of two parts, usually of different size, separated by a narrow space, and provided with independent windings. By varying the relative excitation of the two polar sections, an effective shift of the resultant field flux, and a corresponding change of the direct voltage, is produced.

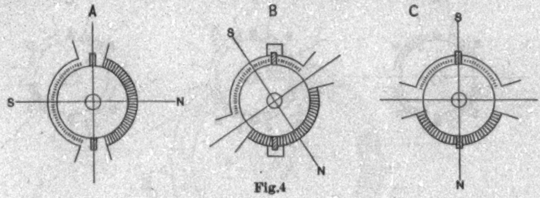

Fig.4

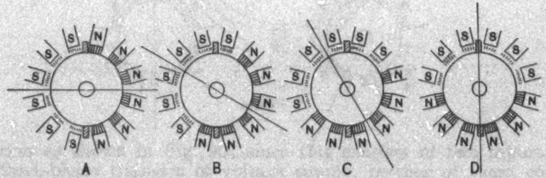

Fig.5

As this method of voltage variation does not depend upon the wave shape, by proper designing of the field pole faces and the pitch of the armature winding, the alternating voltage wave can be made as near a sine wave as desired. Experience shows, however, that the usual distributed winding of the commutating machine produces a sufficiently close approach to sine shape.

*B. Variable ratio by change of wave shape of the star voltage.* If in the converter shown diagrammatically in Fig. 7 the magnetic flux disposition and the pitch of the armature winding is such that the potential difference between the point *a* of the armature and the neutral *O*, or the star voltage, is a sine wave, Fig. 8*A*, then the voltage ratio is normal. Let us assume, however, that the voltage curve differs from sine shape by the superposition of some higher harmonics—the third harmonic in Fig. 8, *B* and *C*, or the fifth harmonic in Fig. 8, *D* and *E*. If, then, these higher harmonics are in phase with the fundamental, as in Fig. 8, *B* and *D*, they increase the maximum of the alternating voltage, and thereby the direct voltage; if these harmonics are in opposition with the fundamental, as in Fig. 8, *C* and *E*, they decrease the maximum alternating voltage and thereby the direct voltage, without appreciably changing the effective value of the alternating voltage. For instance, a higher harmonic of 30 per cent of the fundamental, increases or decreases the direct voltage by 30 per cent, but varies the effective alternating voltage only by $\sqrt{1-0.3^2} = 1.044$, or 4.4 per cent.

The superposition of higher harmonics thus offers a means of

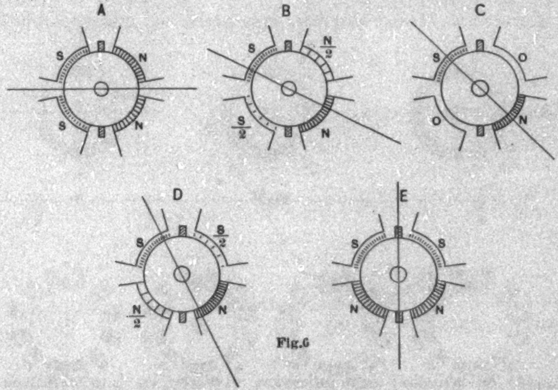

Fig. 6

increasing, as well as decreasing the direct voltage, at constant alternating voltage and without shift of the angle between brush position and resultant magnetic flux.

As, however, the terminal voltage of the converter depends not only on the induced electromotive force of the converter, but also on that of the generator, and is a resultant of the two electromotive forces in approximately inverse proportion of the impedances from the converter terminals to the two respective induced electromotive forces; only such higher harmonics can be used for varying the converter ratio, which may exist in the star voltage, without appearing in the converter terminal voltage.

In general, in an *n* phase system an *n*th harmonic existing in the star voltage does not appear in the ring or delta voltage, as the ring voltage is the combination of two star voltages displaced in phase by $\frac{180}{n}$ degrees for the fundamental, and thus by 180 degrees, or in opposition, for the $n$th harmonic. Thus in a three-phase system, the third harmonic may be introduced into the star voltage of the converter, as in Fig. 8, *B* and *C*, without affecting, or appearing in the delta voltage, and can, therefore, be used for varying the direct voltage. The fifth harmonic can not be used in this way, but would reappear and cause a short-circuit current in the supply voltage, hence should be made sufficiently small to be harmless.

The third harmonic thus can be used for varying the direct voltage in the three-phase converter diagrammatically shown in Fig. 9*A*, and also in the six-phase converter with double-delta connection, as shown in Fig. 9*B*, or double star connection as shown in Fig. 9*C*, since this consists of two separate three-phase triangles of voltage supply, neither of them containing the third harmonic. In such a six-phase converter with double star connection, Fig. 9*C*, the two neutrals must not be connected together, as the third harmonic voltage exists between the neutrals. In the six-phase converter with diametrical connections, the third harmonic of the star voltage appears in the terminal voltage, as the diametrical voltage is twice the star voltage. In such a converter, if the primaries of the supply transformers are connected in delta as in Fig. 9*D*, the third harmonic is short-circuited in the primary voltage triangle, producing excessive currents which causes heating and interferes with the voltage regulation. This arrangement is, therefore, not permissible.

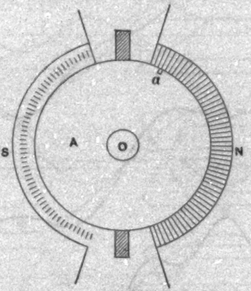

FIG. 7

If, however, the primaries are connected in star, as in Fig. 9*E*, and either three separate single-phase transformers, or a three-phase transformer with three independent magnetic circuits, is used, as in Fig. 10, the triple-frequency voltages in the primary are in phase with each other between the line and the neutral, and thus with isolated neutral cannot produce any current. With a three-phase transformer as shown in Fig. 11; that is, in which the magnetic circuit of the third harmonic is open, triple-frequency currents can flow in the secondary. This arrangement is therefore not satisfactory.

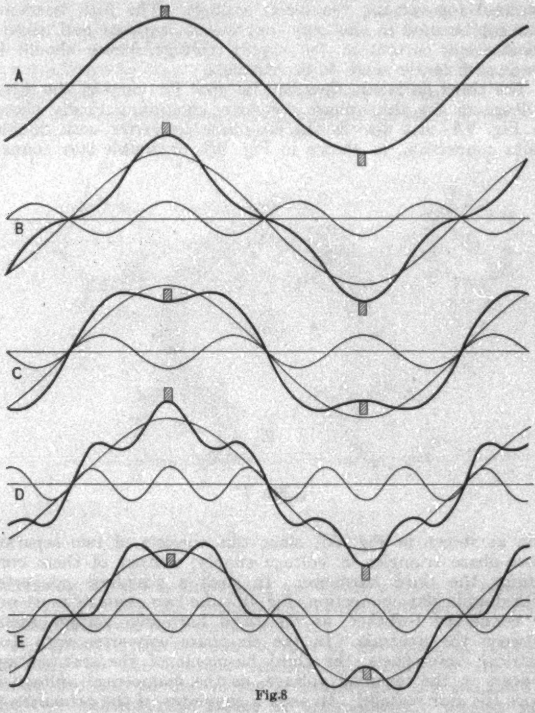

Fig.8

In two-phase converters higher harmonics can be used for regulation only if the transformers are connected in such a manner that the regulating harmonic, which appears in the converter terminal voltage, does not appear in the transformer terminals; that is, by a connection similar to that in Fig. 9*E* and 10.

As the direct voltage regulation of a three-phase or six-phase converter of this type is produced by the third harmonic, the problem is to design the magnetic circuit of the converter so as to produce the maximum third harmonic, the minimum fifth and seventh harmonic.

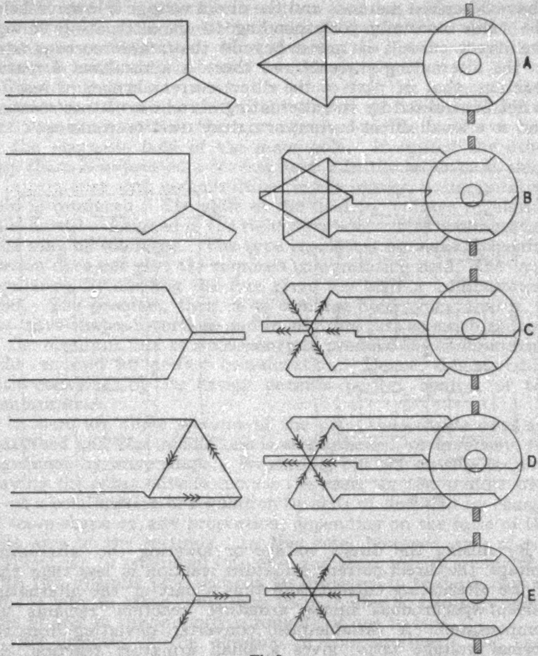

Fig. 9

There are thus two methods of producing a variation of direct voltage at constant alternating supply voltage. We can use either the one, or the other, or a combination of both. Here the question of commutation comes in. In the converter, at normal voltage ratio, the alternating current and the direct current have a fixed ratio, derived from the voltage ratio by the law of conservation of energy. At this ratio, we find that the resultant ampere-turns of the direct-current output equals the resultant ampere-turns of the alternating-current input, neglecting losses and phase displacement, and is opposite thereto. The converter, at normal voltage ratio, has no armature reaction, except the small armature reaction due to the energy current driving the armature round, and the magnetizing or demagnetizing reaction of the lagging or leading current.

Assume, however, that the ratio is changed by any one of the above described methods and the direct voltage is lowered below the value normally corresponding to the alternating voltage; the direct current is raised beyond that value corresponding to the alternating current, and there is a resultant armature reaction; that is, part of the direct-current armature reaction is not neutralized by the alternating current armature reaction, and so a small direct-current armature reaction remains.

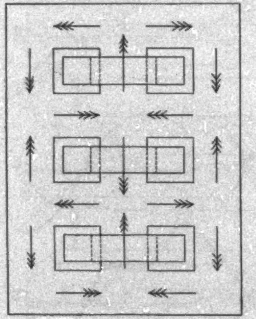

Fig. 10

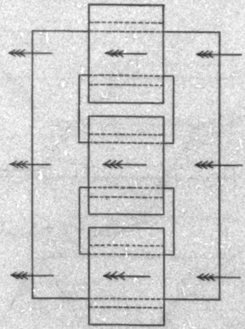

Fig. 11

By raising the direct voltage or lowering the alternating voltage, the direct-current armature reaction is less than that of the alternating current, and thus a part of the alternating current-synchronous motor armature reaction remains uncompensated. A variable-ratio converter, deviating from the normal voltage ratio, gives a small armature reaction, depending on the deviation from the normal voltage ratio, which at raised direct voltage is a synchronous motor reaction; that is, produces a commutating field and so takes care of the commutation; but at lower direct-current voltage it is a direct-current generator armature reaction; that is, tends to impair the commutation by opposing the current reversal. The armature reaction must therefore be taken care of.

In this case of raising the direct voltage, the synchronous motor armature reaction commutates, and if it is not sufficient for the desired commutation, we may shift the brushes to the edge of the next pole. If it should be too high, we can shift the brushes back to the preceding pole. But if we lower the voltage, we get a generator reaction, and therefore need a commutating field. In that case the outer side of the field poles is weakened and the center strengthened, and just where we need the commutating field in the three-part converter—because we have to take care of a generator armature reaction—the field corners weaken. Therefore this type of converter is liable to have poor commutation, when lowering the direct voltage, and thus it is preferably not used for this purpose.

Consider now the type where we may shift the magnetic field electrically. It can be shifted one way or the other. If shifted one way, it means that there is impressed on the brushes a part of the magnetic field of the main pole. If shifted the other way there is impressed a reverse field. In the latter case, there is interference with commutation; in the former, a commutating field is produced. The shift of the field for voltage regulation thus must be designed in the right direction. This commutating field may be too large. The type regulating by wave shape distortion does not give the required commutating field; the type regulating by shifting the flux gives too high a commutating field. The problem, then, is to combine both types; that is, to use wave-shape distortion, and in addition just as much shifting of the resultant flux as is necessary to produce the commutating field required for perfect commutation. Hence, this variable-ratio converter by its design permits perfect control of the commutation.

If there are three sections of the pole, the outside ones are weakened and the middle one is strengthened, or inversely, for regulation by wave shape. Weakening but one outside section, leaving the other outside section the same as the middle one, gives a combination of regulation by shift of flux and by change of wave shape in any proportion, depending on the ratio of the pole arcs of the sections. In this case, however, two of the sections can be combined into one, and there results a converter with two unequal pole sections, as discussed in to-day's papers. This is why in these converters there is used a two-part split-pole of arcs in the proportion roughly of one to two.

This disposes of the question of commutation. The next question is that of output. There is no doubt that if such a machine of 1000 kw. is designed to give any voltage from 200 to 300, it will be larger than an ordinary 1000-kw. machine of constant voltage, as it must be built to produce 300 volts, and to carry current giving the output at 200 volts. This is an inherent feature of all apparatus designed for a range of voltage, whether this range is produced as described above, or by phase control, or by a synchronous generator on the converter shaft, or in any other way.

From what I have said regarding armature reaction, the heating can be understood. At normal voltage ratio, the direct current and alternating current neutralize each other; when raising or lowering the voltage, this slightly modifies the resultant current, and also the heating. Without any further discussion thereof, it may, however, easily be seen that in any case the armature reaction and the excess of direct current over alternating current can never be the same as in the direct-current generator, and the heating thus must remain essentially less than in the direct-current generator, and nearer to that of the standard converter.

**Charles P. Steinmetz** (by letter): *Armature reaction and commutation of variable ratio converter.* With the brushes in quadrature position to the resultant magnetic flux, and at normal voltage ratio, the direct-current generator armature reaction of the converter equals the synchronous-motor armature reaction of the alternating energy current; thus at unity power-factor the converter has no resultant armature reaction, while with a lagging or leading current it has the magnetizing or demagnetizing reaction of the wattless component of current.

*A*. In a variable ratio converter of type *A*, if by a shift of the resultant flux from quadrature position with the brushes, by angle $\tau$, the direct voltage is reduced by factor $\cos \tau$, the direct current and therewith the direct-current armature reaction are increased, by factor $\frac{1}{\cos \tau}$, as by the law of conservation of energy the direct-current output must equal the alternating-current input (neglecting losses). The direct-current armature reaction $F$ therefore ceases to be equal to the armature reaction of the alternating energy current, $F_0$, but is greater by factor $\frac{1}{\cos \tau}$

$$F = \frac{F_0}{\cos \tau}$$

The alternating-current armature reaction, $F_0$, at no phase displacement is in quadrature position with the magnetic flux. The direct-current armature reaction, $F$, however, appears in the position of the brushes, or shifted against the quadrature position by angle $\tau$; that is, the direct-current armature reaction is not in opposition to the alternating-current armature reaction, but differs therefrom by angle $\tau$, and can therefore be resolved into two components:

A component in opposition to the alternating-current armature reaction, $F_0$; that is, in quadrature position with the resultant magnetic flux:

$$F^{\prime} = F \cos \tau = -F_0;$$

that is, equal and opposite to the alternating-current armature reaction and neutralizing it and:

A component in quadrature position with the alternating-current armature reaction, $F_0$, or in phase with the resultant magnetic flux; that is, magnetizing or demagnetizing:

$$F' = F \sin \tau = - F_0 \tan \tau$$

That is, in the variable-ratio converter, the alternating-current armature reaction at unity power-factor is neutralized by a component of the direct-current armature reaction, but a resultant armature reaction, $F'$, remains, in the direction of the resultant magnetic field: that is, shifted by angle $(90 - \tau)$ against the position of brushes. This armature reaction is magnetizing or demagnetizing, depending on the direction of the shift of the field $\tau$.

It can be resolved into two components, one, at right angles with the brushes, and equal:

$$F_1' = F' \cos \tau = F_0 \sin \tau$$

and one, in line with the brushes, and equal:

$$F_2' = F' \sin \tau = F \sin^2 \tau = F_0 \sin \tau \tan \tau$$

as shown diagrammatically in Figs. 12 and 13.

There thus exists a resultant armature reaction in the direction of the brushes that is harmful for commutation, just as in the direct-current generator, except that this armature reaction in the direction of the brushes is only $F_2' = F \sin^2 \tau$; that is, $\sin^2 \tau$ of the value of that of a direct-current generator.

The value of $F_2'$ can also be derived directly, as the difference between the direct-current armature reaction $F$ and the component of the alternating-current armature reaction, in the direction of the brushes: $F_0 \cos \tau$, that is:

$$F_2' = F - F_0 \cos \tau = F\ (1 - \cos^2 \tau) = F \sin^2 \tau = F_0 \sin \tau \tan \tau.$$

The shift of the resultant magnetic flux, by angle $\tau$, gives a component of the magnetomotive force of field excitation $P_2 = P \sin \tau$, where $P$ = magnetomotive of field excitation in the direction of the commutator brushes, either in the direction of armature reaction, thus interfering with commutation, or in opposition to the armature reaction, thus improving commutation.

If the magnetic flux is shifted in the direction of armature rotation; that is, if that section of the field pole towards which the armature moves, as in Fig. 12, is weakened, the component $P_2$ of field excitation at the brushes in the same direction as the armature reaction, $F'$, thus adds itself thereto and impairs the commutation. Such a converter is hardly operative. In this case the component of armature reaction in the direction of the field flux, $F'$, is magnetizing.

If the magnetic flux is shifted in opposite direction to the armature reaction; that is, that section of the field pole which the armature conductor leaves, as in Fig. 13, is weakened, the component $P_2$ of field excitation at the brushes is in opposite direction to the armature reaction $F'$—reversing it if sufficiently large—and gives a commutating or reversing flux $R$; hence improves commutation, so that this arrangement is used in such converters. In this case, however, the component of armature reaction in the direction of the field flux $F'$ is demagnetizing, and with increasing load the field excitation has to be increased by $F'$, to maintain constant flux. Such a converter requires compounding, as by a series field, to take care of the demagnetizing armature reaction.

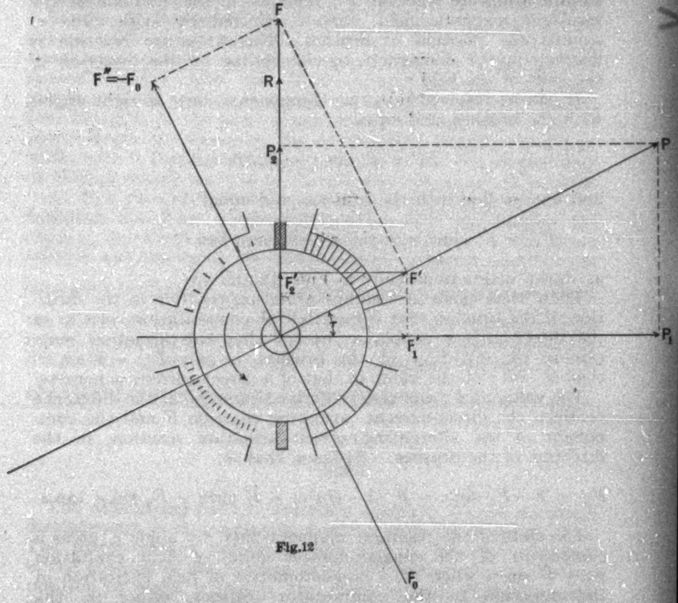

Fig. 12

If the alternating current is not in phase with the field, but lags or leads, the armature reaction of the lagging or leading component of current superimposes upon the resultant armature reaction, $F'$, and increases it, with lagging current in Fig. 12, leading current in Fig. 13; or decreases it, with lagging current in Fig. 13, leading current in Fig. 12. With lag of the alternating current, by phase angle $\tau$, under the conditions of Fig. 13, the total resultant armature reaction vanishes; that is, the lagging component of synchronous motor armature reaction compensates for the component of the direct-current reaction, which is not compensated by the armature reaction of the alternating energy current. It is interesting to note that in this case, as regards heating, output based thereon etc., the converter equals that of normal voltage ratio.

*B.* In a variable-ratio converter of type *B*; that is, operating by wave-shape distortion, let $p$ equal the ratio of direct voltage to that voltage which it would have with the same alternating impressed voltage at normal voltage ratio, where $p > 1$ represents a super-normal voltage, $p < 1$ a subnormal direct voltage. The direct current, and thereby the direct-current armature reaction, then is changed from the value which it would have at normal voltage ratio by the factor $1/p$, since the product of direct volts and amperes must be the same as at normal voltage ratio, being equal to the alternating power input, minus losses.

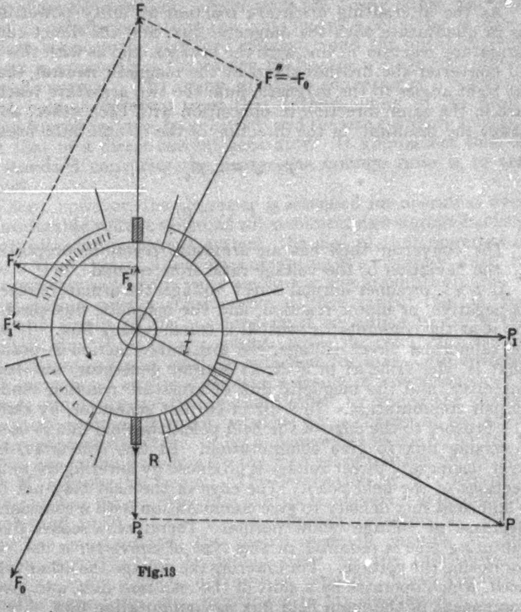

Fig.13

With unity power-factor, the direct-current armature reaction $F$ in a converter of normal voltage ratio is equal and opposite, and is neutralized by the alternating-current armature reaction $F_0$, and at a change of voltage ratio from normal, by factor $p$, thus changing the direct current by factor $1/p$; the direct-current armature reaction is then:

$$F = \frac{F_0}{p}$$

hence leaves an uncompensated resultant.

As the alternating armature reaction at unity power-factor is in quadrature with the magnetic flux, and the direct-current armature reaction in line with the brushes, and as with this type of converter the brushes stand at the magnetic neutral, that is, at right angles to the magnetic flux, the two armature reactions are in the same direction in opposition with each other, and so leave the resultant, in the direction of the commutator brushes:

$$\begin{aligned} F' &= F - F_0 \\ &= F\,(1 - p) \end{aligned}$$

The converter thus has an armature reaction, proportional to the deviation of the voltage ratio from normal.

If $p > 1$, or super-normal direct voltage, the armature reaction is negative, or motor reaction, and the magnetic flux produced by it at the commutator brushes is commutating flux. If $p < 1$, or subnormal direct voltage, the armature reaction is positive; that is, the same as in a direct-current generator, but less in intensity, and the magnetic flux of armature reaction tends to impair commutation. In a direct-current generator, by shifting the brushes to the edge of the field poles, the field flux is used as reversing flux to give commutation. In this converter, however, decrease of direct voltage is produced by lowering the outside sections of the field poles. The edge of the field may not have a sufficient flux density to give commutation with a considerable decrease of voltage below normal. Therefore, a separate commutating pole is required, or this type of converter is used only for raising the voltage. For lowering the voltage the other type is used, which operates by a shift of the resultant flux, and gives a component of the main field flux as commutating flux.

With a polar construction consisting of three sections this can be done by having the middle section at low excitation, and the outside sections at high excitation for maximum voltage. To decrease the voltage, raise the excitation of the center section, but instead of lowering both outside sections, leave the section in the direction of the armature reaction unchanged, while lowering the other outside section twice as much, and so produce in addition to the change of wave shape, a shift of the flux, and thereby produce at the brushes a magnetic commutating field of any desired strength.

The distribution of current in the armature conductors of the variable-ratio converter, and the wave form of the actual or differential current flowing in the conductors, and the effect of the wattless current thereon, are determined in the same manner as in the standard converter, and from them is calculated the local heating in the individual armature turns, and the minimum armature heating.

The results in general are the same, showing a superiority of the six-phase over the two-phase, and of the two-phase over the three-phase arrangement. As regards the rating of the machine based on armature heating, the variable-ratio converter is intermediate between the standard converter and the direct-current generator, approaching the former, the less the voltage ratio differs from the normal. The rating, of such a converter of a constant direct voltage differing from that corresponding to the alternating supply voltage, is far higher, and the size therefore smaller, than that of a direct-current generator. It approaches that of the standard converter the nearer the voltage ratio is to the normal.

Where, however, the converter is intended for operation over a considerable voltage range, as when connecting a storage-battery to an alternating-current system, the size of the converter is greater than that of a converter operating at constant voltage, in the same way and by the same amount as any apparatus intended for operation over a considerable voltage range; that is, the magnetic circuit of the machine must be ample to carry the magnetic flux of maximum voltage, while the conductor section and commutator size must be sufficient for maximum current. This increase of size is a necessary result of operation over a voltage range, irrespective of the method by which the change of voltage is brought about, whether by a change of the alternating impressed voltage, or by a change of the converter ratio, and so has nothing to do with the method of voltage regulation.

**P. M. Lincoln** (by letter): The description by Mr. Steinmetz of the actions taking place in a split-pole converter is beautifully simple and lucid. I fail to see, however, wherein Mr. Steinmetz has substantiated the claims made in opening his discussion; namely, that he would clear up the difficulties in regard to commutation, decrease in capacity, lower efficiency, variable wave form, etc., mentioned in my discussion.

As to the three-part-pole machine, the reduction in capacity necessary to obtain a reasonable voltage variation seems to put this type of machine out of the running entirely. As to the two-part-pole machine, Mr. Steinmetz has failed to reconcile the conflicting requirements of wave form and commutation. Wave form demands that the commutating notch in the field be of zero width. Commutation, on the other hand, demands a notch in the field form of at least 20 per cent to 25 per cent of the space between brushes. This has been demonstrated by years of experience. Just how much will be required under the peculiar conditions of the two-part-pole construction is problematical, but it is impossible for me to conceive how it can be less than in a machine of normal design; and in view of the variable field strength at the commutating point, it seems that this notch should be considerably wider than in the normal design. In fact the necessarily wide variations of field strength at the commutating point raise serious questions as to the possibility of obtaining satisfactory commutation even with the most favorable notch widths.

I am deeply interested in Mr. Steinmetz's description of the variable-voltage converter, and I give mental assent to every one of his deductions, but I am disappointed that he does not explain away the above questions as well as the others raised by my discussion.

In closing his discussion, Mr. J. L. Woodbridge takes issue with my statement that rapidity of voltage change can be largely increased in the separate alternating-current booster converter over anything possible in the split-pole machine, owing to the possibility of omitting dampers from the separate booster field, coupled with the impossibility of omitting them from the split-pole machine. He suggests that I did not take into consideration that in the case of a separate alternating-current booster the strength of the main converter fields, (which must be damped) as well as the booster fields, must change before the voltage ratio of the combination can change. I wish to assure Mr. Woodbridge that I fully considered the matter in this light before making my statement. It is perfectly true that so long as its speed remains constant, neither the alternating nor the direct voltage of a converter can change without changing its field strength. Immediately upon a change in the voltage applied to the alternating current end of a converter, a current begins to circulate through its armature of such a nature as to cause the field value to change rapidly to that necessary to accommodate the changed alternating current value. The whole power of the system to which the converter is attached is available for bringing about this change in field flux. If the shunt field of the converter is excited from its own commutator, the shunt ampere-turns will assume a new value such as will, with proper design, virtually eliminate the armature current which causes the immediate adjustment of the field flux. It is the duty which falls upon the regulator that determines its speed of action, and in the case of the separate booster converter, the changing of the flux in the main converter fields is not a part of this duty. This condition was all gone over mentally before making the statement appearing in my discussion. I considered it so obvious as not to require statement.

Mr. Woodbridge further states that he has designed a damper to apply to the split-pole machine of such a nature that it does not interfere materially with the speed of voltage changes. To cause voltage changes in a converter of Mr. Woodbridge's design, a shifting of magnetic flux from one part of the pole-face to another is required. To prevent hunting, a damper must be so designed as to prevent the shifting of magnetic flux from one part of the pole-face to another. Mr. Woodbridge's requirement is, therefore, diametrically opposed to the essential object of a damper. I must, therefore, remain skeptical as to the efficacy of the new damper until further details are disclosed.

**J. L. Burnham** (by letter): Since the papers and discussions so far have been theoretical, it may be of interest to have some results from machines that have been built. The results given are based on observations of the operation of one 200-kw. three-phase; one 500-kw. six-phase; and four 1000-kw. six-phase converters all having a range in voltage of 4 to 5; a 1000 kw. converter having a 6 to 7 voltage range; and a 2000-kw. six-phase converter having a range in voltage of 2 to 3. None of these machines had unusual armature winding pitch or tap connections to eliminate harmonics, as suggested in the papers by Messrs. Adams and Woodbridge, since all experimental data obtained showed that it was not necessary.

These machines were operated from a 13200-volt, 2000-kw. alternator over a one-half mile line through transformers connected delta primary, double-delta secondary; delta primary, diametral secondary; star primary, diametral secondary; star primary, double-delta secondary; and two-phase primary, six-phase, double-T secondary. When running at no load, the alternating-current minimum input for various excitations throughout the voltage range did not in any case exceed 8 per cent, except for the delta primary, diametral secondary connection of transformers. This 8 per cent alternating-current input includes all of the odd harmonics, except the third and its multiples, which are eliminated by transformer connections, in addition to no-load losses of the machine, which would amount to about 3 per cent. This result seems to confirm the calculated negligible value of harmonics given in the papers by Messrs. Adams and Woodbridge. At full load these harmonics are so small that they do not make an appreciable difference between kilovolt ampere and kilowatt readings.

The 200-kw. and 500-kw. machines mentioned above have passed the probation period of two years mentioned by Mr. Lincoln and Mr. Waters and have shown themselves to be the equal of machines with usual pole construction in general operating characteristics, such as commutation, stability, alternating-current and direct-current starting, quiet running, etc. The efficiencies are, of course, dependent upon the voltage for each load. For voltages obtained by operating the two sections of the pole with excitation in the same direction, there is virtually no difference between sectional-pole machines and the machine of standard pole construction. When the auxiliary section is excited to reverse polarity of the main section, the core-loss and loss in armature conductors, due to load current, will be greater than for a machine of standard construction, amounting at extreme lower voltage to between 1 and 2 per cent. It will, therefore, be seen in the table given later that the split-pole machine will be more efficient at the higher voltages of its range than the converter with a pole-piece of usual construction and its induction or booster regulator, and approximately the same efficiency at the lower voltages of the range.

In regard to three-wire operation, it may be stated that this has been successfully accomplished with transformers connected star primary, diametral secondary, deriving the neutral from the transformers. Throughout the 3 to 4 range of voltage, with an unbalancing between the two sides of 70 per cent of the full load current of the machine, the machine was perfectly stable, commutating sparklessly and running quietly. The harmonic currents were negligible and the direct-current voltage steady. This is a guaranteed condition of operation.

Mr. Waters's statement that a slight displacement of poles of the split-pole machine from their proper position would cause excessive equalizing current to flow in a multiple-wound armature has no weight, since the same result would be obtained from the displacement of poles of the usual construction or with interpole construction.

No mention has been made of the performance of a split-pole converter as a compound-wound machine. From tests made on a machine having a two-section pole with shunt winding on the main pole and a series winding on the auxiliary pole, an overcompounding of approximately 15 per cent. was obtained without taking a wattless component of current in excess of that given at approximately 98 per cent. power-factor full load the alternating voltage at collector rings being held constant. With the usual arrangement of compound-wound converters with 15 per cent reactance coils in the collector lines, a variation in wattless component of over 100 per cent would be required to give the same overcompounding. Assuming that the shunt field is excited to give 50 per cent of the full-load current lagging at no load, the leading wattless component at full load would be somewhat in excess of 50 per cent full-load current, which would give a power-factor in the converter of less than 90 per cent. In addition to the advantage of running at practically unity power-factor with a compound-wound split-pole converter, the commutation will be fully as good when the machine is operating with rotation such that the auxiliary pole will be on the leading side of the main pole, as with the reverse, or usual rotation. With proper proportions of auxiliary field, the commutation may be improved by depending upon the auxiliary pole for commutating flux, which will be proportional to the load, the same as in a commutating pole machine. The auxiliary section will then serve as a commutating, as well as a compounding pole.

In the following table approximate costs, floor space, and efficiencies, are based on 1000-kw. units with a voltage range 4 to 5, all to meet the same guarantees. The machine of usual pole construction with induction regulator is taken as the basis for comparison.

CONVERTER WITH USUAL POLE CONSTRUCTION

| | With induction regulator per cent. | With revolving armature a.c-booster per cent. | With revolving field a.c-booster per cent. | Split pole converter per cent. |
|---|---|---|---|---|
| Cost.................. | 100 | 112 | 106 | 100 |
| Efficiency mid-voltage full-load.......... | 94.5 | 94.25 | 94.5 | 95 |
| Weight.............. | 100 | 106 | 106 | 97 |
| Floor space............ | 100 | 103 | 107 | 96 |

**J. L. Woodbridge**: Professor Adams has presented a very interesting discussion of the theory of the split-pole converter, differing in many respects from mine. A comparison of the two methods of analysis will show that while starting from the same point, namely, the harmonic analysis of the curve of field distribution, they both arrive at practically the same conclusions by two different routes and they therefore fit in very well together. In each analysis certain points are covered which do not appear in the other.

There are one or two points brought up by Mr. Lincoln to which I would like to refer. He has called attention to the limited width of the neutral space for commutation shown in Fig. 17 of my paper. It must be understood that Fig. 17 shows the field distribution at the armature periphery including the field fringe, and the distance between the pole tips would therefore be greater than the 30° space shown in this Fig. In fact this Fig. was taken from a machine actually designed, built, and operated. This question of commutation has, however, been so thoroughly covered by Dr. Steinmetz and by Mr. Burnham, from both theoretical and practical standpoints, that further comment appears unnecessary.

In comparing the split-pole converter with a series alternating-current booster, Mr. Lincoln has taken the stand that the latter would act more quickly, owing to the fact that there is a smaller amount of field flux to change. Mr. Lincoln does not seem to have taken into account the fact that with a converter having an alternating-current booster mounted on the same shaft, if it is desired to vary the direct voltage without altering the alternating voltage or the power-factor, it will be necessary to vary the fields of both machines. It is impossible to vary the direct voltage of the converter without changing its field strength. While this may be brought about without changing the excitation of the field windings, by simply changing the voltage applied to the collector rings and permitting the wattless current thus produced in the armature to magnetize or demagnetize the field, nevertheless this change of field strength must be brought about. The voltage at the brushes cannot be reduced without actually reducing the flux through which the armature winding is passing. Some reduction in excitation will result from the reduced voltage applied to the shunt-field winding of a self-excited converter, but unless a prohibitive amount of iron is used in the magnetic circuit, so as to work below the knee of the saturation curve, this change in excitation will produce but little effect on the field strength, and the remainder must be produced by wattless currents in the armature. Such a combination cannot, therefore, operate at unity power-factor without providing for simultaneous control of both fields.

In regard to damping devices, I would say that a special design of damper has been worked out for the three-part pole, which will not interfere with the quickness of action. It permits the field flux to vary symmetrically with respect to the axis of the field, while retarding any tendency to shift the entire field one way or the other. For the two-part field the main section can be provided with an ordinary copper-ring damper, since the field strength in this section is not varied. Where the auxiliary field section is controlled automatically, no damping device will be required, as the automatic controller will counteract any tendency to a variation of flux in this section, other than that which is required for operation.

Many of Mr. Lincoln's objections to the split-pole converter appear to be based on the assumption that it is impossible to eliminate the higher harmonics from the wave form. In this connection it may be well to emphasize what has already been brought out in this discussion; namely, that the variation of voltage ratio in the split-pole converter is not dependent upon these higher harmonics, but that these are merely incidental, and their elimination by a proper design of the machine does not limit the change of ratio obtainable. In the three-part pole the third harmonic determines the voltage ratio, but this does not appear in the wave form with three-phase connection. In the two-part pole it is the shifting of the entire field that produces the change of voltage ratio, and this result may be obtained with a pure sine wave of fundamental frequency, as has been so clearly shown by Dr. Steinmetz. Mr. Burnham has also shown that in the machines of this type actually built, these harmonics are quite negligible, even without the introduction of special features in the design adapted to minimize them.

**G. E. Brown** (by letter): Referring to Fig. 25, a test made on a 1000-kw. converter of the two-part-pole type recently put into commercial service, gave data very similar to that indicated in these curves. The converter was operated at no load with constant alternating voltage, and the direct voltage varied from 185 to 310. The normal direct voltage is 270, which requires no current in the auxiliary field circuit.

Referring to the statement that the minimum disturbance of power-factor occurs when working on either side of *Fo* as shown in Fig. 15, it is also evident from Fig. 25 that less change in the main field current is necessary to hold unity power-factor when the converter is operating below normal voltage than when it is operating above normal voltage. In this test, with the converter operating at no load from 185 to 270 volts, it was found that a variation in the main field current of about one per cent was necessary in order to maintain unity power-factor.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 1, 1908.*

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# A NEW LARGE GENERATOR FOR NIAGARA FALLS

BY B. A. BEHREND

A new generating plant of considerable magnitude has been completed recently at Niagara Falls. This plant is the new plant of the Niagara Falls Hydraulic Power and Manufacturing Company. A number of large direct-current generators to be used for the manufacture of aluminum has been installed in this plant, each generating unit consisting of two direct-current generators connected to 11,000-h.p. turbines. A large alternating-current generator, one of an aggregate of three wound for 12,000 volts, has also been installed in this station. The power house is located at the foot of the falls, on the American side, below the old power house of the Niagara Falls Hydraulic Power and Manufacturing Company.

The generator which is described in this paper offers a number of interesting features and is remarkable among the generators at Niagara Falls on account of its speed of 300 rev. per min., which is greater than the speed of any of the other large generators installed in the power houses at the falls. The generator is wound for 12,000 volts, three-phase, 25-cycles. The waterwheel is mounted on a horizontal shaft and has a capacity of 11,000 h.p. The generator is rated at 6500 kw. with a capacity for continuous operation of 7320 kw., or approximately 7500 kw. The runaway speed of the waterwheel is given as 500 revolutions; the generator, therefore, had to be designed to be safe at this speed.

The experience which has been gained from the design of generators for direct connection to steam turbines has greatly minimized the difficulties of a problem like the one under consideration. Nevertheless, 11,000-h.p. generating units are neither so plentiful nor so readily designed and built as not to afford considerable interest, especially if the results obtained with such machines are remarkably satisfactory.

The object of this paper is to illustrate, by a number of photographs and drawings, the design and construction of this interesting unit, and to show by the tests the electrical characteristics.

Fig. 1 shows the generator assembled on the test floor.

Fig. 2 shows the stator of the generator with the rotor removed.

Fig. 3 shows the rotor by itself.

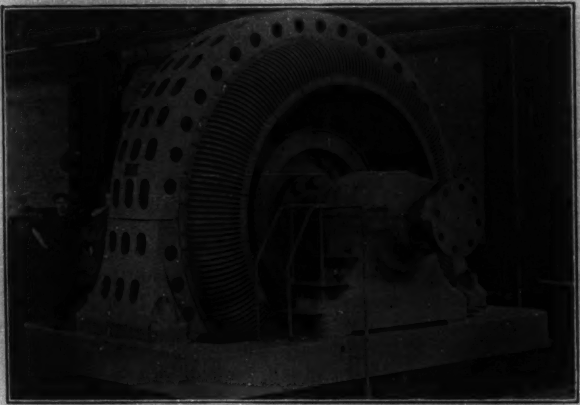


Fig. 1—10,000 h.p. generator

Fig. 4 shows one of the pedestals and the two stands for supporting the brush studs for the field excitation. The field excitation is derived from 220 volts.

Fig. 5 is an assembly drawing showing the most important details.

The construction of the rotor is worthy of careful study. A disc of nickel-steel, without a hole in the centre, forms the middle part of the revolving element. Two nickel-steel rings are mounted on each side of this web and are bolted and keyed to it. The nickel-steel used for this construction must have great mechanical strength and high magnetic permeability. A nickel-steel containing 3.5 per cent. nickel has been used for this purpose. Its elastic properties are.

| | |
|---|---|
| Elastic limit | 50,000 lb. per sq. in. |
| Ultimate strength | 80,000 lb. per sq. in. |
| Elongation | 20 per cent. in 2. in. |
| Reduction of area | 40 per cent. |

The magnetic qualities of this steel are given in the curve illustrated by Fig. 6. The nickel-steel forgings as used in this construction enable the designer to produce the strongest and lightest construction, as the mechanical strength of the material is great and the magnetic permeability high. The weight of the complete rotor is only 92,900 lb. and, the bearings being 16 in. by 50 in., the specific pressure is only 58 lb. per sq. in. The weight of the stator is 116,700 lb. and the weight of the entire machine is 275,000 lb.

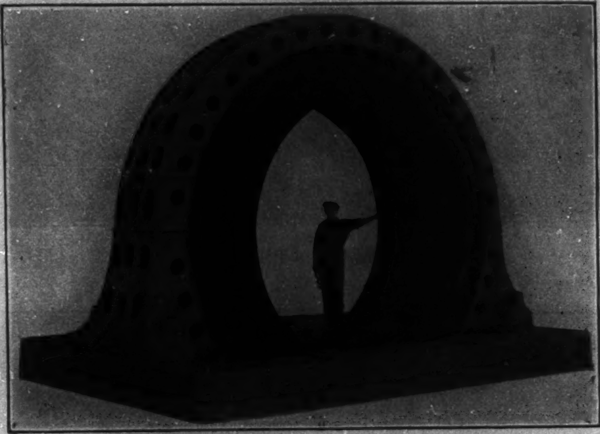


Fig. 2—Stator of 10,000 h.p. generator

It may be of interest to discourse briefly upon the theory of elastic stresses in rotating discs and rings. The theory of

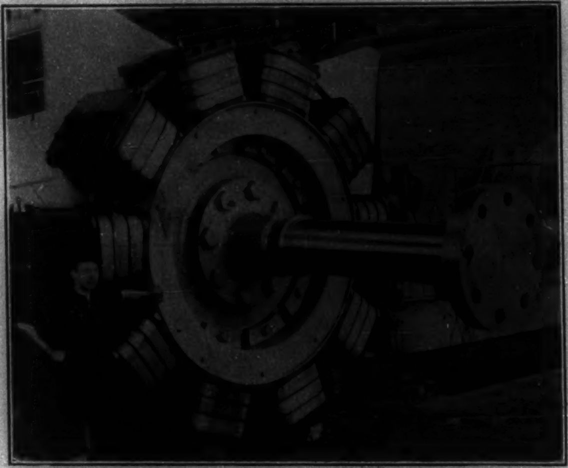


FIG. 3—Revolving field of 10,000 h.p. generator

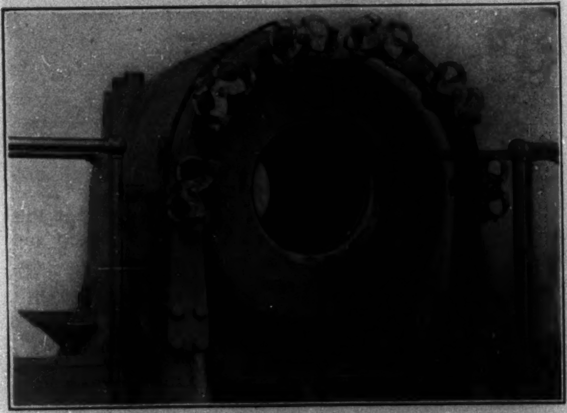
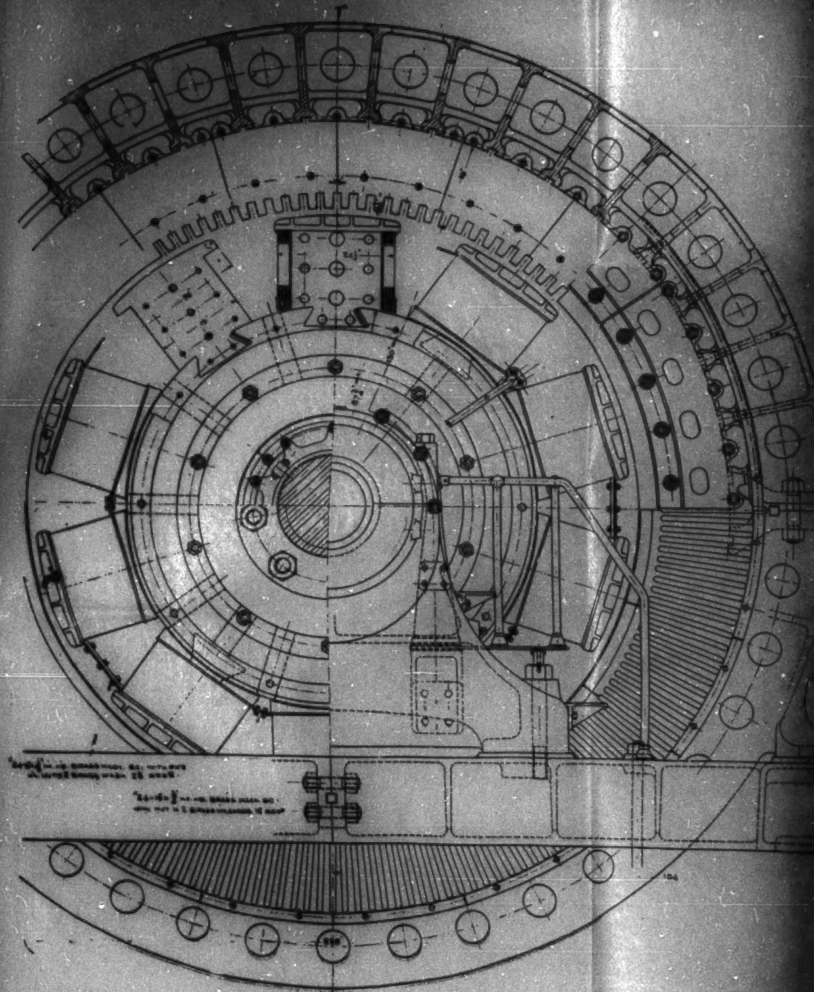


FIG. 4—Pedestal and brush stands of 10,000 h.p. generator



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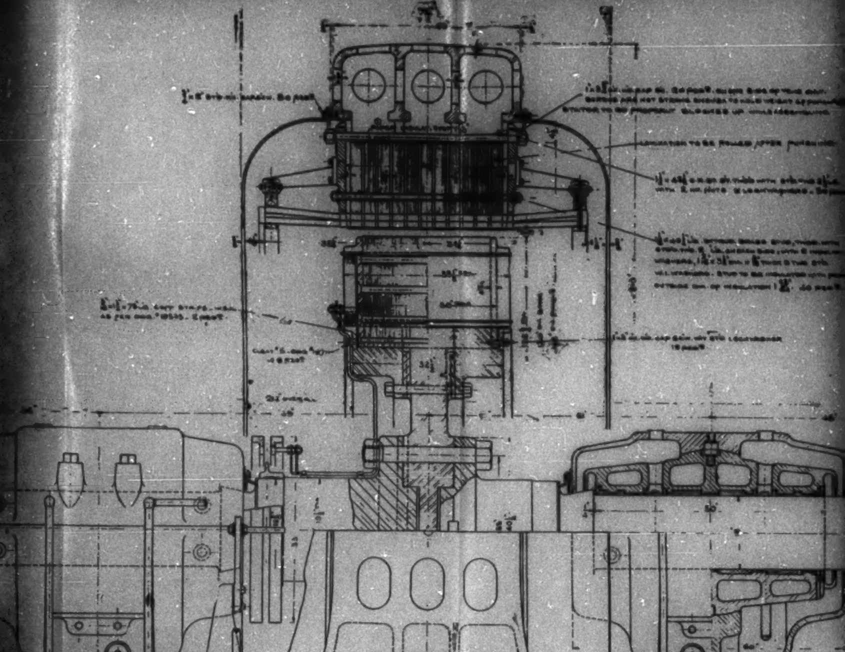


10,000 h.p. generator

elasticity applied to the radial and tangential stresses in rotating discs shows that the point of maximum stress is at the centre of a disc and at the inside surface of a ring. We have demonstrated the correctness of this theory by experiments with lead discs, the deformation of which, as obtained by measurement before and after the test, readily indicates that the maximum deformation, as shown by the lateral contraction, appears at the centre of the discs or at the inside of the ring from where the metal flows toward the outside portions. The radial stress normal to a free surface must be zero, and, therefore, the maximum

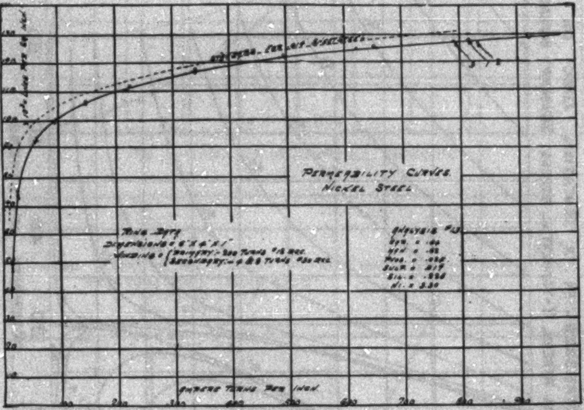


FIG. 6

stress appears as a tangential stress. In a solid disc the elements at the centre are subject to both radial and tangential stresses. A hole in the centre eliminates the radial stress, and, as is shown by the theory, this doubles the tangential stress. This is well illustrated in the curves shown in Fig. 7, in which the radial stresses are shown by the abscissas on the left of the curve sheet, and the tangential stresses are shown by the abscissas on the right of the curve sheet. It is assumed that the outside radius of the disc, or the ring, is kept constant and equal to 10 units of length, while the inside radius is increased from zero to 10 units of length. The radial and tangential stresses are then represented by the abscissas of the two sets of curves shown in the figure. Great mechanical strength and lightness are obtained in this rotor construction, and although it would have

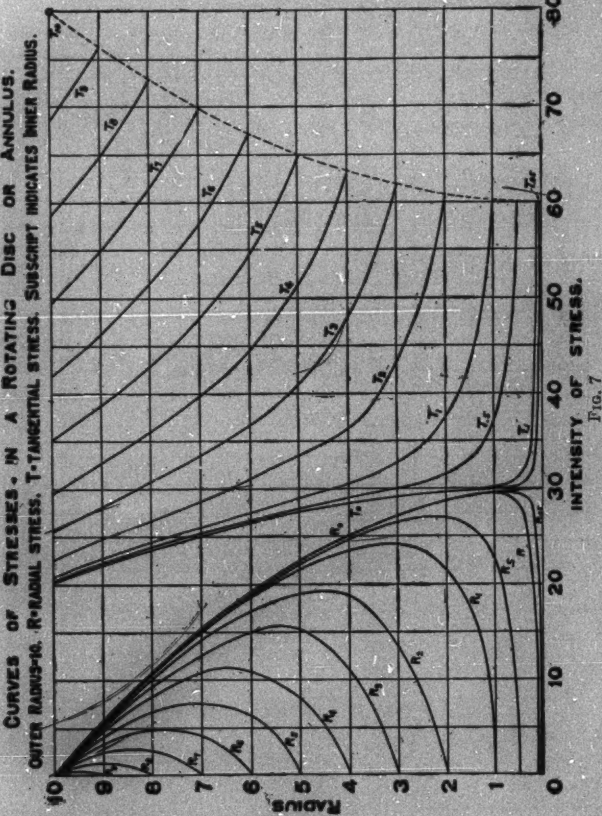


Fig. 7

been possible to use a hub mounted on a shaft, according to the practice with slow-speed machinery, as the stresses on the inside of the hub would not have been prohibitive, the design adopted

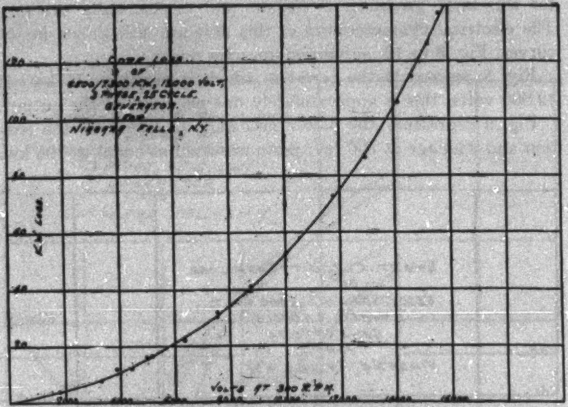


FIG. 8—Core loss of 10,000 h.p. generator

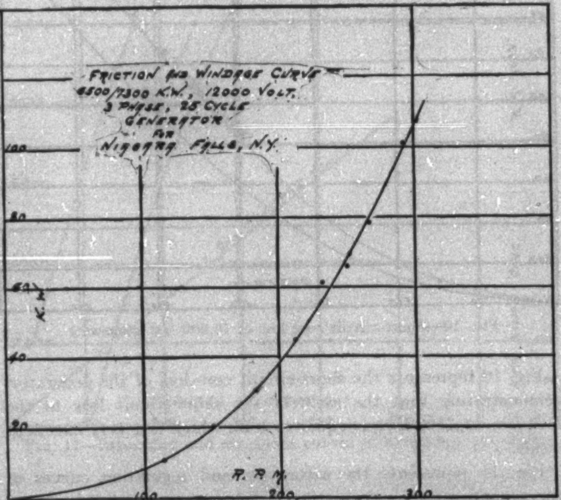


FIG. 9—Friction and windage curves of 10,000 h.p. generator

for this large generator is elegant and mechanically superior. The electrical characteristics of this unit are well shown in the curves, Fig. 8 to 12, accompanying this paper.

Fig. 8 represents the core-loss which is equal to 75 kw. at 12,000 volts; this is approximately one per cent. of the output.

Fig. 9 represents the power necessary to overcome the friction and windage at 300 rev. per min. which is equal to 106 kw.

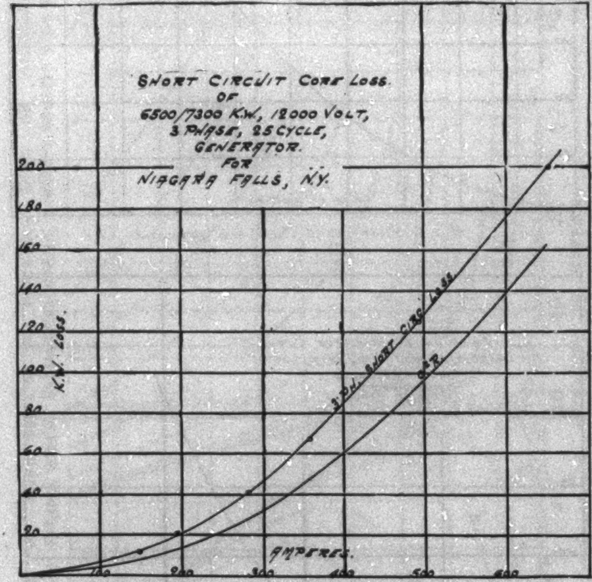


FIG. 10—Short-circuit core loss of 10,000 h.p. generator

Fig. 10 represents the short-circuit core-loss of the generator, demonstrating that the ratio of the short-circuit loss to the $I^2 R$ loss, at 7500 kw., is equal to 1.45, which is a very excellent result.

Fig. 11 represents the saturation and regulation curves of the generator with a regulation of 8.4 per cent. at full load and 100 per cent. power-factor at 12,000 volts. The generator is

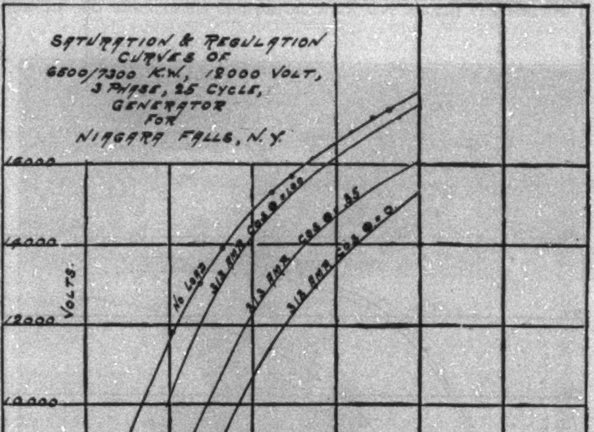
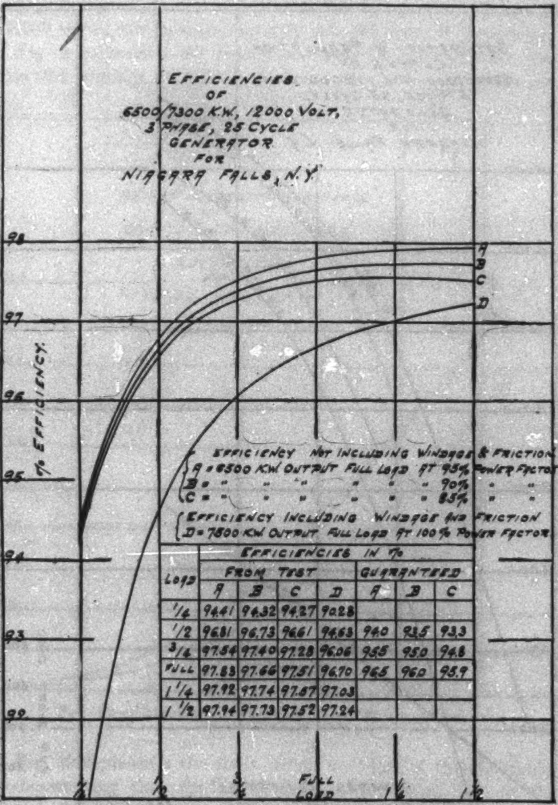


FIG. 11—Saturation and regulation curves of 10,000 h.p. generator


EFFICIENCIES OF 6500/7300 K.W., 12000 VOLT, 3 PHASE, 25 CYCLE GENERATOR FOR NIAGARA FALLS, N.Y.

EFFICIENCY NOT INCLUDING WINDAGE & FRICTION
A = 6500 K.W. OUTPUT FULL LOAD AT 95% POWER FACTOR
B = " " " " " " 90% " "
C = " " " " " " 85% " "

EFFICIENCY INCLUDING WINDAGE AND FRICTION
D = 7500 K.W. OUTPUT FULL LOAD AT 100% POWER FACTOR

| LOAD | EFFICIENCIES IN % | | | | | | |
|---|---|---|---|---|---|---|---|
| | FROM TEST | | | | GUARANTEED | | |
| | A | B | C | D | A | B | C |
| 1/4 | 94.41 | 94.32 | 94.27 | 90.28 | | | |
| 1/2 | 96.81 | 96.73 | 96.61 | 94.63 | 94.0 | 93.5 | 93.3 |
| 3/4 | 97.54 | 97.40 | 97.28 | 96.06 | 95.5 | 95.0 | 94.8 |
| FULL | 97.83 | 97.66 | 97.51 | 96.70 | 96.5 | 96.0 | 95.9 |
| 1 1/4 | 97.92 | 97.74 | 97.57 | 97.03 | | | |
| 1 1/2 | 97.94 | 97.73 | 97.52 | 97.24 | | | |

FIG. 12—Efficiency curves of 10,000 h.p. generator

capable of giving 13,000 volts under any condition of load that is likely to occur, should this be required.

Fig. 12 shows several efficiency curves and a tabulation of the guaranteed efficiencies compared with the actual efficiencies.

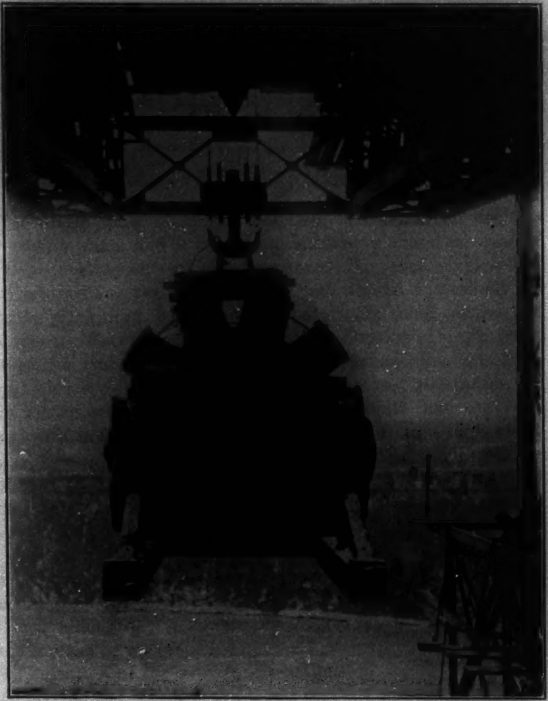


FIG. 13—Revolving field on its way down the cliff

Fig. 13 shows the revolving field suspended from a crane from the cliff, 240 ft. above the Niagara River, as it was being lowered into the gorge.

From the tests made regarding the heating of this unit, the temperature will remain within 35 degrees at normal load and 40 degrees at 7500 kw. The power of this generator is going to be used chiefly for the operation of induction motors in Niagara Falls and its vicinity.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N.J., July 1, 1908.*

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# MODERN DEVELOPMENT IN SINGLE-PHASE GENERATORS

BY W. L. WATERS

The single-phase alternator has been in commercial use now for twenty years and it may seem surprising that there should be new developments at this late date. However, single-phase alternators have been used in the past almost exclusively for lighting work, and in units of comparatively small output and low speed. Recently, on account of the adoption of single-phase current for traction work, an important demand has arisen for large high-speed, low-frequency, single-phase generators. It is in the design and manufacture of such units that the engineer has had to overcome new difficulties. In large, high-speed, single-phase generators for 15 and 25 cycles the difficulties met with are due almost entirely to the large pole-pitch and high armature reaction which it is necessary to adopt. A 500-kw., 60-cycle, 72-pole, single-phase generator would have a pole-pitch of about 7 in., while a 6000-kw., 15-cycle, 2-pole machine would have one machine of about 120 in. It is easily seen that the design of these will be radically different.

These difficulties in single-phase generators of large pole-pitch are the result of:

1. Pulsation of the armature reaction.
2. Mechanical stresses on the end-connections of the armature coils.

The pulsation of the armature reaction causes hysteresis and eddy-current losses throughout the machine, often resulting in dangerous heating and low efficiency. The mechanical stresses due to the current in the ends of the armature coils result in vibration and distortion of the windings, and often in damage to the insulation or complete destruction of the coils, these stresses being particularly serious in single-phase railway generators, on account of the sudden variations in load and numerous short-circuits to which these machines are subjected. As the effect of the mechanical stresses on the armature coils, and the losses due to the pulsation of armature reaction, practically increase proportionally to the square of the pole-pitch in generators of standard design, it is easily seen why these effects which were negligible in the old single-phase alternators of small pole-pitch have become quite serious in the modern turbine-driven generator. The seriousness of these difficulties when they were first met with was so great that even within the last two years responsible engineers have stated it was impossible to build satisfactory low-frequency, high-speed, single-phase generators of large capacity, and it is only by careful study and experimenting that the modern machine of this type has been developed.

*Losses due to pulsation of armature reaction.* In a polyphase generator the armature current produces a magnetic flux which rotates synchronously with the field magnet. This magnetic flux being of practically constant magnitude, causes very little loss in the iron of the magnetic circuit. On the other hand, the armature current in a single-phase generator produces a pulsating magnetic flux which is stationary in space. It is easily seen that this pulsating flux will cause hysteresis and eddy-current losses throughout the whole magnetic circuit. The exact effect of the armature reaction flux on the rotating magnets depends, of course, on the relative phase of the armature current and electromotive force; that is, on the power-factor of the load on the generator. When the power-factor is unity and the armature current is in phase with the electromotive force, the armature reaction flux is a cross-magnetization; when the power-factor is zero and the armature current is 90° out of phase with the electromotive force, the armature reaction flux is a demagnetization. In the special case in which the rotating field magnet is cylindrical, without projecting poles, the effect of the armature reaction flux on the magnets is, of course, more nearly independent of the power-factor of the armature current. But in any case this flux is a pulsating one, and there are important losses in the field magnets, due to their rotation through this pulsating cross-flux or demagnetization flux.

An estimate of the combined losses in the armature and field magnets due to the pulsating armature reaction can be obtained in a number of ways. We can measure the increase of the power required to rotate the field magnets due to normal root-mean square current in the armature coils, with:

1. Direct current in the armature.
2. Alternating current of synchronous frequency in the armature.
3. Armature short-circuited and field excited.

Or with the magnets stationary we can:

4. Send normal frequency alternating current through the armature and measure the losses by a wattmeter.

These methods must all be regarded as convenient tests which are found by experience to give a good indication of the magnitude of the losses. Method (4) has the additional advantage that we can vary the relative position of the armature reaction flux and the pole faces, and thus investigate the variation of the losses in a single-phase generator with the power-factor of the load.

The only exact methods of measuring the losses are:

1. As unknown losses in a motor-generator-method efficiency test, or
2. From a comparison of the temperature rise obtained on full load with that obtained with known losses.

Unfortunately, both of these tests are difficult to make accurately, especially on a large machine, and probably in practice they do not give results which are any more accurate than the other methods. So at the present time we have to acknowledge that though we know a great deal about the relative values of the losses under various conditions, our knowledge of their absolute values are only approximate.

*Pole-face dampers.* Losses caused by a pulsating flux in the magnetic circuits are due to:

1. Hysteresis.
2. Eddy currents.

And the relative magnitudes of the two depend on the amount of solid metal in the path of the flux. If the whole magnetic circuit is laminated, then the losses are practically all due to hysteresis. On the other hand, if we have solid cast-steel poles there will be eddy currents in these poles which will partly choke back the pulsation of the flux and the hysteresis loss will be reduced. But in this case there will be eddy-current losses in addition to the hysteresis, and the way in which the total loss is changed will depend on the proportions and design of the magnetic circuit. If we place a heavy copper damper in the path of the pulsating flux, this will provide a low-resistance path for the eddy currents, and the pulsating flux, and consequent hysteresis loss, will be reduced practically to zero, while on account of the low resistance of the damper circuit the eddy loss will not be appreciable. The way in which the losses and the pulsating flux vary according to the presence of eddy currents can be determined for any particular design by changing the thickness of the laminations, or changing to solid poles or dampers. It is usually found that the losses are greatest with heavy laminations or solid poles; that they are less for thin laminations, and practically zero when heavy low-resistance dampers are used either with solid or laminated poles.

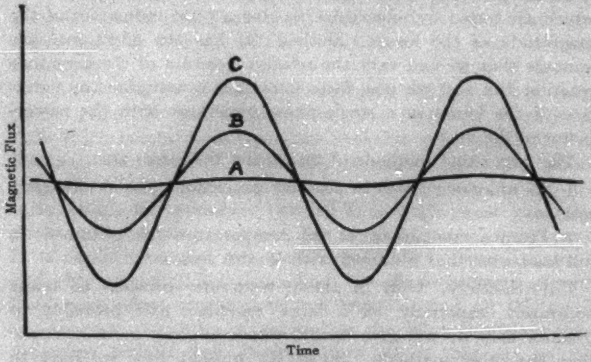

Fig. 1

Fig. 1 shows the pulsation of the armature reaction flux in a 500-kw., single-phase, 20-pole generator, as determined by means of search-coils wound on the pole-faces. "*C*" shows the pulsation for laminated poles, No. 29 gauge: "*B*" shows the same machine with solid poles: "*A*" shows the same solid pole faces covered with a $\frac{3}{8}$-in. copper plate. The magnitude of the pulsations in the three cases is about in the ratio of from 30 to 15 to 1; thus the copper plate has practically damped out all pulsations, the armature reaction flux becoming constant. In practice, a copper damper usually takes a form similar to the squirrel-cage secondary of an induction motor. Heavy copper bars are dovetailed into the pole faces, and short-circuited at the ends by copper rings or discs. Fig. 2 shows such a cage damper on the field magnet of a 6000-kw., 2-pole generator.

The question of losses due to the pulsating armature reaction in a single-phase generator may be considered in another and possibly a simpler way. The single-phase pulsating field is equivalent to, and produces the same effect as, two rotating fields each of half its maximum value, one rotating at the same speed and in the same direction as the generator field magnet, and the other rotating at the same speed but in the opposite direction. The flux rotating synchronously with the field magnet, being constant in magnitude, causes very little loss. The flux rotating in the reverse direction causes losses throughout the whole magnetic circuit due to hysteresis and eddies. If we have a squirrel-cage damper enclosing the field magnets, this damper system acts in regard to this reverse rotating flux in the same way as the short-circuited secondary of an induction motor or transformer, a current is induced in the damper which produces a field that neutralizes the rotating flux. The eddy and hysteresis loss in the iron of the magnetic circuit which would be caused by this rotating flux is thus eliminated, and the only loss is that due to the current circulating in the damper. If we make the conductors forming the squirrel cage of sufficiently low resistance, this damper loss becomes negligible, with the result that the entire loss due to the pulsating armature reaction of the single-phase generator is practically eliminated.

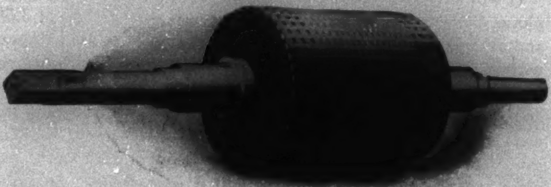

FIG. 2

To show how serious this matter of losses becomes in two-pole single-phase machines without dampers, the following table is given, showing the losses and full-load temperature rises on three turbo-generators, both with and without dampers:

TWO-POLE, 25-CYCLE, SINGLE-PHASE GENERATORS. SAME CURRENT PER ARMATURE CONDUCTOR ONE AND THREE-PHASE UNDER ALL CONDITIONS AND ALL LOSSES IN PER CENT. OF SINGLE-PHASE RATING

| Size | Type field | Three phase |  | Single phase |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  | Without dampers |  | Without dampers |  | With dampers |  |
|  |  | Loss | Temperature | Loss | temp. | Loss | temp. |
| 750 kw. | Solid | 0.53 | 27°c. | 3.75 | 95°c. | 0.8 | 34°c. |
| 1000 kw. | Solid | 0.3 | 31°c. | 3.0 | 122°c. | 0.5 | 37°c. |
| 1000 kw | Laminated | 0.2 | 19°c. | 3.8 | 150°c. | 0.3 | 18°c. |

It will be seen that in these three machines, operating single-phase, there is due to the pulsating flux an average loss of 3.5% and an average temperature rise of 125° cent., without dampers; with dampers the average loss is 0.5% and the temperature rise 30° cent. Figures are given only on comparatively small machines on account of the difficulty of measuring losses on large machines. But tests on larger generators up to 6000-kw. capacity show that the improvement due to heavy copper dampers is even more striking in large machines than it is in small. So far as experience goes at the present time, it may be said that the use of such dampers is the complete solution of the difficulties due to pulsating armature reaction met with in large, low-frequency, two-pole, single-phase generators.

*Mechanical stresses on armature coils.* That it was necessary mechanically to brace the end-connections of the armature coils on a direct-current machine subjected to sudden loads and short-circuits has been known for many years. But until quite recently additional supports for alternator armature coils were seldom provided. The reason for this was that as the continuous short-circuit current of an alternator is only about two or three times normal, it was not considered that the mechanical stresses on the ends of the small pole-pitch coils generally in use were sufficiently great to cause any trouble. Only during the last few years has it been demonstrated by experience that coil supports on large pole-pitch alternators are not only advisable but necessary, and that on account of the numerous short-circuits, they are particularly necessary on single-phase machines operating on traction circuits.

When an alternator is suddenly short-circuited, the first rush of current is limited only by the self-induction in circuit. In the case of an alternator of very low self-induction, this first rush of current on sudden short-circuit will be 15 or 20 times normal full-load current. As the mechanical stress on the end-connections varies as the square of the current, this means that the stress on the armature coils is 200 to 400 times normal. A 6000-kw., 2-pole, 25-cycle, single-phase generator will have a pole pitch of about 100 in., and the length of the end-connection at one end of one armature coil will be about 180 in. We find that the mechanical stresses on the end-connections at one end of one armature coil of this machine on a sudden short-circuit is something like five tons; and we usually find that on low-frequency high-speed generators of large capacity the mechanical stresses on the end-connections at one end of one armature coil on sudden short-circuits are from 2 to 10 tons. When we consider that this comes as a sudden mechanical shock on the winding, we can realize the kind of coil supports that are required, and can understand the disastrous results sometimes obtained on short-circuits, when such supports are omitted.

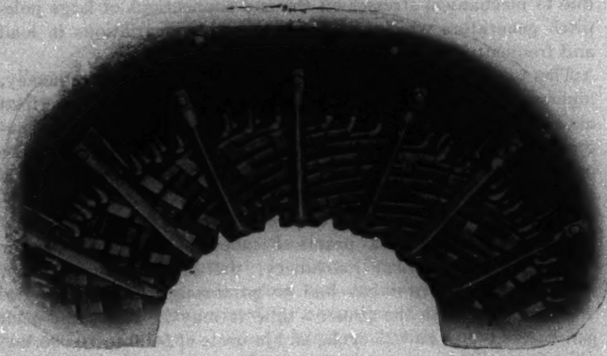

FIG. 3

We can see from these stresses that coil supports must be of metal of heavy cross-section. The objections to metal are, of course, those of insulation, but though coil supports of wood, porcelain, and similar insulating materials have been tried, it is easily understood that they have proved unsatisfactory on machines of large pole pitch. Fig. 3 shows a form of coil support which has been developed and proved satisfactory. It is of bronze and of heavy girder, section and insulated for the full generator voltage. The coil support and its method of application are evident from the illustration; it is placed in position after the machine is wound and is removable in a few minutes at any time. It is not suggested that this is the only satisfactory type of coil support that can be used; it is given as a type which has proved successful in actual operation on machines up to 10,000-kw. capacity, and it has apparently solved the difficulties due to mechanical stresses on the end-connections of large pole-pitch generators which are liable to sudden variations in load and frequent short-circuits.

The two main difficulties met with in large low-frequency, high-speed, single-phase generators, which have been described above, can at the present time be regarded as having been successfully overcome. The use of heavy copper dampers on the pole faces and heavy bronze coil supports applied to the ends of the armature coils in such a way as to take directly the mechanical stresses which develop on short circuits, have now made such machines a practical success. Like every other new type of electrical machinery, the large turbine-driven, single-phase generator has had to go through a period of development, but at the present time it may be said that such generators for 15 and 25 cycle, and in units of 5000 to 10,000 kw. capacity can be, and are, built with the same success as that obtained on standard slow-speed polyphase generators.

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# APPLICATION OF FRACTIONAL PITCH WINDINGS TO ALTERNATING-CURRENT GENERATORS

BY JENS BACHE-WIIG

Fractional pitch windings have been treated by various authors in the past, especially with regard to the influence they have upon the self-induction of the armature winding. The object of this paper is to deal briefly with the points leading to the use of a chorded winding for alternating-current generators from the standpoint of manufacture and design, and to indicate the influence this winding has on the performance of a machine.

*Reasons for chording the winding.* In general, the chorded winding has been adopted to facilitate the manufacture of armature windings. As generators are manufactured, there are certain standard frames used for a number of ratings at different speeds and voltages. Group windings, with the number of slots per pole per phase equal to an integer, are generally preferred, and the number of conductors is fixed within a limited range for a given voltage. This often necessitates the use of a chorded winding in order to get the proper effective number of conductors. This is especially the case for low-voltage machines of large size. Further, a winding often works out in such a way that a better arrangement of conductors in the slot can be obtained through chording. A two- or a four-pole high-speed generator is another example where the chorded winding facilitates manufacture. Such a machine will naturally have a comparatively small bore, and if open slots and form-wound coils are used, it is impossible with a coil-throw equal to the pole pitch to bring the coil through the bore of the armature without bending it entirely out of shape. The only solution, therefore, is to chord the winding a sufficient amount to allow it to pass through the bore. In this case, therefore, the chorded winding is of great advantage, as it permits the use of form-wound coils. This may not hold in cases where the coils are made in halves.

With regard to the construction of the end-connections of form-wound armature coils for large alternating-current generators, especially for a generator with a small number of poles, the space occupied by the end-connections is considerably smaller for a chorded winding than it is for pitch, even taking into account the increased number of armature conductors made necessary by the chord. The effect of chording upon the number of armature conductors is to increase the number in the ratio of the sine of half the electrical angle between the two sides of the coil, whereas the length of the end-connection and the distance the coils build out decreases directly in proportion to the electrical angle. The result is a saving in space. This is of particular benefit to all two-pole machines, but applies also to four- and six-pole machines above 500 kw. It may also be of advantage to chord the winding for these reasons for smaller machines when wound for high voltage.

Take, for example, a 300-kw. 11,000-volt three-phase 500-rev. per min. 25-cycle generator. This machine has six poles, and with six slots per pole per phase will have 108 slots total. Having form-wound coils with the coil-ends extending in a parallel plane to the shaft, one coil per slot, and a pitch winding (1 and 18) the distance between the armature iron and the extreme end of the coils is approximately 16.5 in. Between adjacent coils 0.25 in. air space is provided. Chording this winding down to 1 and 14, or 130 electrical degrees, reduces the above distance to approximately 14.9 in. or decreases the width of the machine 3.2 in. The same winding arranged for two coils per slot, builds out approximately 20.5 in. for pitch winding and 16.75 in. for throw 1 and 14. This means a 7.5 in. reduction in all-over width of the machine. The width of the armature iron being 8 in., it can readily be seen that this insures relatively large saving in space. As indicated by the above dimensions, the winding with two coils per slot extends farther beyond the armature core than does the winding with one coil per slot, and, accordingly, chording the winding is more advantageous for a two-coil-per-slot winding.

As stated above, space can be saved in the way the coils build out even for a six-pole, 300-kw. machine. As space is saved, the mean length of one armature turn is reduced. On the other hand, the number of conductors on the armature is increased, and thus a certain throw will give the most efficient winding in regard to copper loss and amount of copper. Taking the above mentioned 300-kw. generator and working it out on the basis of equal iron losses, with one coil per slot there is practically no difference in the weight of copper with different throws—the decrease in length of mean turn is balanced by the increase in the number of turns. With two coils per slot there is a saving of approximately 25% in the weight of copper and of copper loss in favor of the chorded winding having coils lying in slots 1 and 14 over the pitch winding having coils lying in slots 1 and 19. The gain by reducing the throw, therefore, amounts to gaining space for the one-coil-per-slot winding only, and means a saving in space and a reduction in copper loss and weight of copper as well for the two-coil-per-slot winding.

As mentioned above, the winding with two coils per slot builds out farther than does the winding with one coil per slot, and the comparison between the pitch winding and the chorded winding will, therefore, show up more in favor of the winding with two coils per slot.

As the six-pole 300 kw. generator here referred to is a comparatively small machine, it is evident that for large generators, or generators with a smaller number of poles, the above figures will show up still more favorably for the chorded winding; the example indicates that even down to this size of machine it is advantageous to chord the winding.

One may say that chording the winding is to take the copper out of the end-connections and put it in the slots, which is another point in favor of the chorded winding, for it is easier to get rid of the heat in that part of the coil which is imbedded in iron than it is to cool the end-connections of the winding. The ventilating conditions, therefore, are often improved by chording. As above stated, this applies particularly to large machines and windings having a comparatively large throw.

It is stated above that the length of the end-connections decreases in proportion to the chord and that, even if the weight of the copper is not decreased, the chording has the effect of decreasing the amount that the coil-ends build out. As the question of bracing the coil-ends of a generator with a small number of poles and a large throw is of great importance, it will readily be seen that shortening the end-connections is a great benefit in this respect; it makes them stiffer, so that even if coil supports are used, both in the case of pitch winding and chording, the chorded winding is superior in mechanical strength.

It may be argued in connection with the above that a chorded winding requires heavier insulation of the end-connections than does a pitch winding as the phases are intermixed and points of higher potential are brought together. As a rule it is true that a chorded winding, will have more points of higher potential between adjacent coils than will a pitch winding, but considering that the coil-ends for larger generators always should be arranged with an air-space between adjacent coils, and further that they are braced and prevented from touching one another, in only extreme cases will it be necessary to provide for any extra heavy insulation. In an ordinary pitch winding, points of high potential are brought together at the beginning of the phases. As a rule no extra heavy insulation is provided for at such points. Considering the part of the coil lying in the slot, even if the full-line voltage exists between two coils in one slot, it should not cause any trouble as each coil is already insulated against ground.

*The effect of chorded winding upon armature reaction.* As, for a given voltage, the effective number of turns must be the same whether the winding is pitch or chorded, the effective number of armature ampere-turns is also the same in both cases; consequently the demagnetizing effect will remain practically unchanged. The chord, however, has an influence upon the self-induction of the machine. This effect is very much the same as in the case of an induction motor, a subject considered at length in a paper read before the Institute.* The reducing influence of the chording upon the slot leakage, the tooth-tip leakage, and the coil-end leakage, as pointed out in that paper, could be applied to similarly wound alternating-current generators. In many cases, however, the self-induction does not have much influence upon the short-circuit ratio, as it is small compared with the demagnetizing ampere-turns, and, consequently, a change in self-induction will not change the short-circuit ratio to any extent, so that in ordinary cases the self-induction can be figured without considering the chord. There are cases, however, where the decrease of the self-induction due to the

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* Fractional Pitch Windings for Induction Motors, by C. A. Adams, W. K. Cabot and G. A. Irving, Jr., Niagara Falls, June 28, 1907.

fluence of the chording upon the slot leakage, the tooth-tip

chording of the winding has to be carefully considered. One such case is when a delta connection is used for a three-phase generator with chorded winding with two coils per slot. It is a well known fact that when the wave-form is not a sine, the third harmonic present in such a winding causes current to flow round the delta. In most cases these currents are small and the loss due to them is negligible. This, however, does not hold in the case referred to; for as the same current flows in the three legs of the delta through all the coils in succession the slot and the tooth-tip leakage is eliminated for those slots in which the current flows in opposite directions, thus reducing the self-induction of the circuit. The self-induction, however, is the main thing that opposes the flow of this current, and thus it can easily be seen that when the chording of a delta-connected winding is carried out in such a way that the third harmonic is

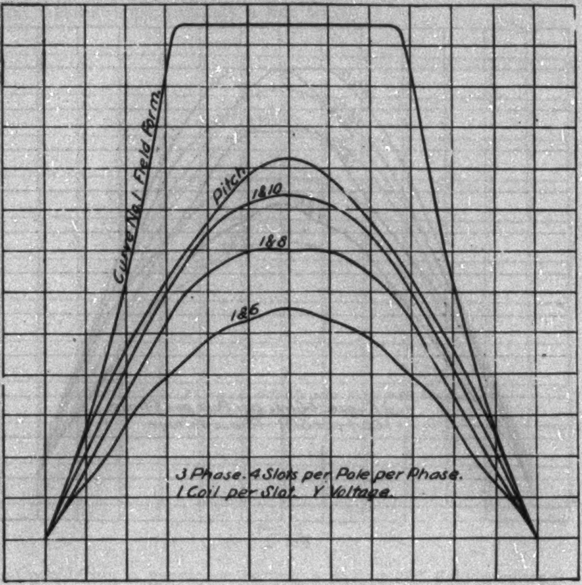

Fig. 1

present in the winding, it will set up an internal circulating current. A one-coil-per-slot winding with the same chording will have far less influence upon the local currents flowing, as in this case the sides of the coils opposing each other do not lie in the same slots.

It may be added that the chording of a two-coil-per-slot winding has also some influence upon the eddy-current losses set up in the armature conductors. As is well known, eddy-current losses are set up in the conductors, and, in cases of large copper section are considerable. The chording has the effect of bringing conductors belonging to different phases into the same slots, and thus the currents flowing in these conductors are not in phase, which again tends to reduce the eddy-current losses.

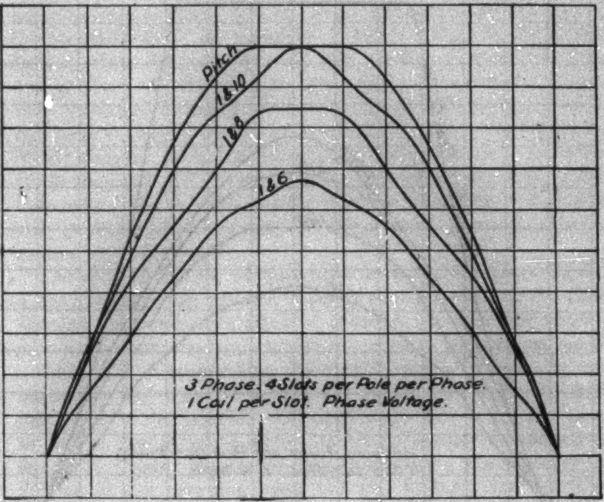

FIG. 2

*The effect of the chorded winding upon the wave-form.* If the field form of the generator follows a sine wave, the chording of the armature winding will not change the form of the electromotive force wave; the wave-form will remain a sine wave. The more the field form departs from the true sine wave, the more will the influence of the chord show up in the shape of the wave-form. In the case of high-speed generators with a small number of poles, it is often, for mechanical reasons, not possible to bevel the poles at all, or else it is not possible to bevel the poles in such a way as to give a smooth field form approximating a sine curve. At the same time a generator having a small number of poles will usually have a large number of slots per pole per phase, so that this will tend to smooth out the wave-form and make it approximately a sine wave.

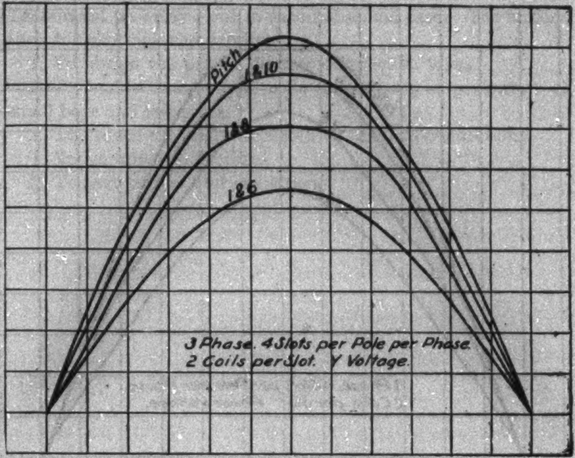

FIG. 3

Considering a generator having a cylindrical field construction, as in the case of a two-pole turbo-generator, the field form will be approximately as shown in Fig. 1, curve 1. For this filed form the electromotive force wave-forms are plotted in Fig. 1 for a three-phase Y-connected winding having four slots per pole per phase; the wave forms are plotted for pitch winding and for chord winding: 1 and 10, 1 and 8, and 1 and 6. It will be seen that the chord 1 and 10 improves the wave-form, but that 1 and 8, and 1 and 6, are distorted.

For the same winding and the same throws, the wave-forms of each leg are plotted in Fig. 2; these wave-forms would also be obtained when connecting the winding in delta. As is to be expected, these wave-forms are in all cases considerably more distorted than those shown in Fig. 1 and indicate the influence of the higher harmonics.

Figs. 3 and 4 show the wave-forms for the same field forms and same number of slots per pole per phase when the winding is connected in Y and delta, but with two coils per slot. As the phases by these combinations are more distributed over the pole face, the wave-forms are less distorted than for the one-coil-per-slot winding; in the case of the Y connection the shape of the wave approximates as nearly a sine for the chord 1 and 6 as it does for the pitch winding. The wave-forms in Fig. 4, however, show evidence of higher harmonics of similar nature, but less pronounced than the one-coil-per-slot winding, Fig. 2.

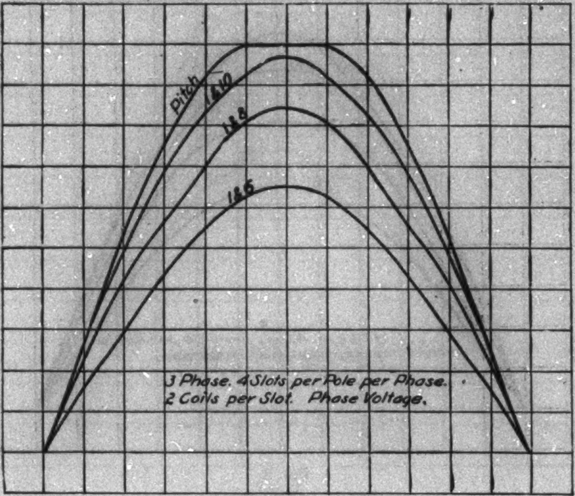

Fig. 4

As noted above, these wave-forms are plotted for a nearly rectangular field-form. It is therefore evident that the chord has a more pronounced influence upon the wave-form than would be the case if the field form would more nearly approximate a sine curve. However, it is evident that the chord does have an influence upon the wave-form, and when chorded windings are used the wave-form should, therefore, be considered.

*Conclusion.* In determining the most efficient amount of chording, so many points are to be considered in each case that no general rules can be formulated. In cases where the chord is not made necessary solely for mechanical reasons, the most efficient chord will depend upon the number of poles, the ratio of pole-pitch to pole-length, the voltage, and the size of machine. These must be worked out in each individual case. The reasons then for chording the winding are;

1. To obtain the proper number of effective turns.
2. To enable form-wound coils to be used in generators of small bore and few poles.
3. To reduce the space occupied by the end-connections.
4. To improve ventilation.
5. To save copper and insulation.

## DISCUSSION ON "A NEW LARGE GENERATOR FOR NIAGARA FALLS", "APPLICATION OF FRACTIONAL-PITCH WINDINGS TO ALTERNATING-CURRENT GENERATORS", AND "MODERN DEVELOPMENTS IN SINGLE-PHASE GENERATORS." ATLANTIC CITY, N. J., JULY 1, 1908

**Wm. J. Foster:** There are two or three points in connection with the generator described by Mr. Behrend to which I would like to call attention. I think that in many respects it is a most remarkable machine. The efficiency as given by Mr. Behrend in the tabulation is something unusual, when we consider that it is a generator of 12,000 volts. I would like to point out how, in my opinion, the high efficiency has been attained.

The writer of this paper has given us a complete assembly drawing. It seems to me that it will be of great value to the professors and representatives of our educational institutions to have such complete data giving every essential dimension. From the curves showing the characteristics, taken in connection with the assembly drawings, it is apparently possible to reproduce the windings exactly. The first thing I notice is the remarkably small amount of magnetic material in the armature, which results in a rotor of unusually small weight, considering the output of the machine. Mr. Behrend has taken a step in advance over all other designers in this respect. The reduction of magnetic material is something that is to be striven for and that can be accomplished, provided we can take care of the heating, which is what has troubled all of us heretofore. The amperage in the slots of this armature is very high, considering the potential, but Mr. Behrend says the temperatures are very low, hence it would appear that the problem has been solved.

A word further with reference to the efficiency. What used to be called the electrical efficiency is evidently given, but it does not include a percentage of the load losses. It simply includes the core losses, which, according to the curve, are 75 kw., or only about one per cent.

The efficiency is unusually high, and has been attained, in my judgment, by using an extremely high armature reaction for a 12,000-volt machine. If you increase the armature reaction twenty-five or thirty per cent, as I consider has been done in this case, you attain a very high efficiency, much higher than has been attained heretofore. But this requires a different design of the rotor, involving a heavier pole. It is evident on the face of it that the pole must be of greater length, to take care of the increased ampere turns. It must be lengthened about as the square of the ampere turns, hence I consider the pole forty or fifty per cent longer than the usual type. This lengthening can be accomplished only by an unusually strong construction in the rotor, which Mr. Behrend dwells upon in his curves pertaining to the peculiar disc construction and in his discussion of the characteristics of the nickel steel. I am especially glad to see that nickel steel can also be obtained of such high permeability. This is another thing which appeals to the designer as a step forward, namely, to be able to obtain nickel steel with high characteristics mechanically, and at the same time very high in its magnetic properties.

In the matter of windage, I am somewhat disappointed in this machine. The curve showing the variation of the friction and windage with the speed is a peculiar one. You will notice how rapidly these factors go up with increased speed. At 300 rev. per min. it is nearly five times what it is at half that speed. If it continues to go up at that rate it will take 300 or 400 kw. to drive the generator at the runaway speed. It seems to me that eddies exist and that the most of the windage is really lost, as far as cooling effect is concerned. What takes place as the speed increases is that a new set or system of eddies is established, requiring more and more energy to enable the speed to be obtained. When we take into account the friction and windage losses in connection with the electrical losses and the load losses, it seems to me there is not very much gain in commercial efficiency on this machine.

The reduction in magnetic material does result in assisting the problem of the bearings, but the bearings must be very conservative with the pressure per square inch as mentioned, and the rubbing speed so conservative. This same diameter of shaft is in use on many generators running at 400 revolutions with which I am acquainted. Hence, the bearings problem in this Niagara generator is not especially difficult.

**B. A. Behrend:** I have made the efficiency on the basis of short-circuit and core losses, but not including friction and windage, one-third of the short-circuit losses.

**Wm. J. Foster:** In working up efficiencies it has been customary to take one-third of the short-circuit losses as the "load losses." I think the Institute should appoint a committee to consider whether that is the correct value to take for the load losses.

**L. Schuler** (by letter): When the first large turbo-alternators for single-phase current were designed about two years ago by the Felten & Guilleaume-Lahmeyerwerke, the question of avoiding losses by the pulsating armature reaction was carefully considered. It was clearly understood that a minimum of losses could be attained either by perfectly laminating the field or by providing heavy dampers, but we were at that time not quite sure which way would be best. We therefore made the following experiment: An ordinary three-phase induction motor with slip-rings was coupled to a direct-current motor and used as a single-phase generator by exciting one stator-phase with direct current. The other two stator phases could be connected to a variable resistance. Two slip-rings were short-circuited so that the whole arrangement represented a

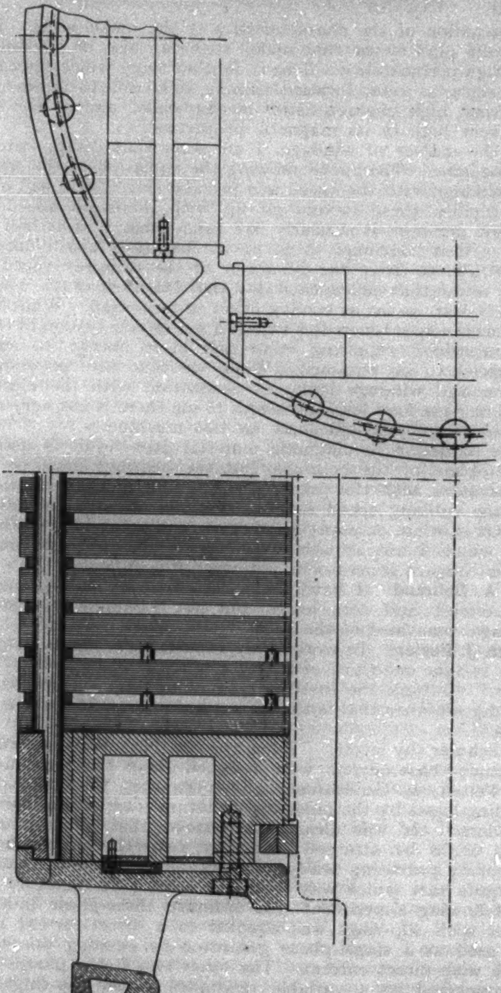

FIG. 1

single-phase generator with stationary laminated field, working under short-circuit. The two stator phases not used for excitation acted as "dampers" when short-circuited. By opening these phases or closing them through the variable resistance it was possible to work the generator with perfectly laminated field or with dampers of variable resistance. The losses were determined by the energy consumed by the direct-current motor. The curve, Fig. 1, was taken with constant armature current. It shows clearly that with single-phase load the hysteresis loss in a perfectly laminated field is much larger than the total hysteresis and eddy-current loss with low-resistance dampers, We therefore used heavy dampers in all single-phase generators,

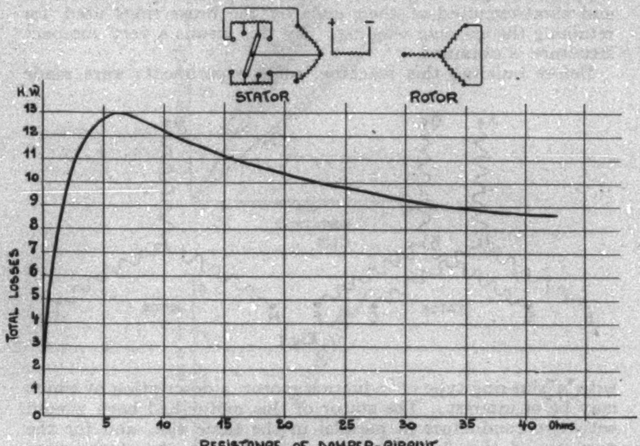

Fig. 2

for which we adopted the design shown in the sketch, Fig. 2, which has given full satisfaction.

**F. H. Clough** (by letter): I have read Mr. Waters's paper with considerable interest, as probably most of us who have attempted the design of single-phase generators for coupling to steam turbines have experienced the difficulties described and have endeavored to eliminate the deleterious effects of single-phase armature reaction. As the author suggests, the simplest way of looking at the matter is to regard the armature magnetization as consisting of two components, each of half the maximum value and revolving in opposite directions.

If the rotor is provided with a complete squirrel-cage winding, the machine can then be regarded as a single-phase squirrel-cage induction motor. The currents in the rotor bars under these conditions are such that taken in conjunction with the armature reaction of the stator a uniformly rotating field is produced. If the machine be assumed to be running at synchronous speed, the rotor will be stationary with regard to the field, and, therefore, an additional exciting winding supplied with continuous current can be placed on the rotor. By this means we come to the single-phase alternator as described in the paper.

The company with which I am associated recently built a 1,000-kw. generator of this type, and its operation has been entirely satisfactory. The squirrel-cage winding consists of copper bars carried in slots round the periphery of the rotor and short-circuited at their ends by the brass rings used for retaining the exciting winding. By this means a very compact structure is obtained.

Before building this machine, some experiments were made with a slip-ring type of induction motor, a description of which may be of interest. The stator of this motor had been wound with two conductors in parallel in the same slot, and for the purposes of this test these two windings on the stator were kept entirely separate. Fig. 1 shows the arrangement of the windings. Exciting current was supplied through the winding *A J B* and single-phase current taken from the two slip-rings of the rotor *G* and *H*. The other winding *D E F* of the stator was short-circuited through ammeters. The short-circuit rotor current produced for a given excitation with and without the winding *D E F* closed is shown in Fig. 2. In Fig. 3 is shown the single-phase short-circuit core loss with and without this winding short-circuited. The short-circuit current in winding *D E F* agreed very closely with the value expected, and consequently allowed the size of the squirrel-cage winding on the main alternator to be accurately determined.

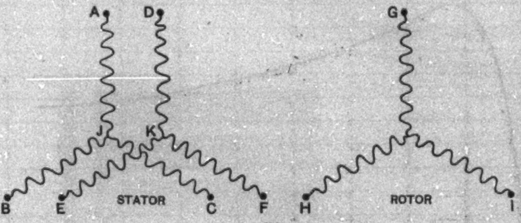

Fig. 1

I agree with the author that this squirrel-cage winding forms a complete solution to the troubles experienced with single-phase turbo-generators. In addition to the reduction in the core loss, it will be noticed from Fig. 2 that the reactance has been reduced to a very great extent, so that a machine with this type of rotor—apart from the $I^2 R$ losses in the squirrel-cage winding, which are small—can be wound to give the same output three-phase or single-phase with approximately the same efficiency and regulation.

With regard to the second portion of the paper, the method of securing the stator coils, although apparently mechanically sound, appears to be open to two objections: first, the difficulty of ventilation, although perhaps this may not be serious; second, that the coils are set back a long way from the rotor. This location of the coils would tend to increase the self-induction of the latter considerably, as, although the medium surrounding the coils is only air, still the area of the magnetic path for a machine such as the one described by the author is very big, and it will probably be found that such a winding causes a considerably higher self-induction than a winding

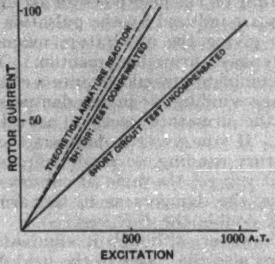

Fig.2

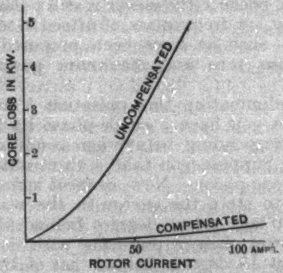

Fig.3

which is brought out in the form of a barrel closely surrounding the end connections of the rotor.

**Chas. P. Steinmetz:** Since the question of single-phase alternators has come up, I desire to call attention to another way of accomplishing the same result of operating a single-phase load on a big alternator, without the objectionable features of the single-phase machine. This way is by using a polyphase alternator, that is, making the machine polyphase and storing the energy of the quadrature-phase.

The arrangement discussed by Mr. Waters is essentially a squirrel-cage winding on the field poles, or an equivalent thereto, in which currents are induced by the pulsation of the armature reaction, thereby giving the quadrature magnetomotive force, that is, the polyphase armature reaction. Theoretically, to effect this result completely would require a copper cross-section in the squirrel-cage winding, or in the dampers, infinitely large compared with the armature section, as otherwise you get additional losses. If you give the dampers the same total section as the armature winding, to produce quadrature polarization, it means that you get the same (or, at any rate, not greatly differing) losses in the dampers as in the armature; in other words, you about double the $I^2 R$ loss.

This method, however, although it eliminates the pulsation of the field, and so also the losses in the field due to pulsation, does not eliminate pulsating strains on motor shaft and revolving machine, because the power is still pulsating; and where you come to very low frequencies, of fifteen to ten cycles, in very large machines, such as have been proposed, the enormous pulsation between zero and maximum power may become objectionable.

One way of eliminating this pulsation I will outline very briefly. Suppose you have a single-phase load of, say, thirty degrees lag, corresponding to average conditions of a single-phase railroad. Suppose you take a three-phase machine and put the load on one phase. Now, connect across another phase a reactive coil, to store the energy in the reactance. In the load the current lags thirty degrees behind the voltage, and the curve of power then is pulsating with double frequency, with a maximum 15 degrees behind that of the voltage. The electromotive force in the reactive coil is lagging behind the electromotive force on the load by 60 degrees, being the other phase. The current in the reactive coil lags 90 degrees behind its electromotive force, and the power of the reactive coil being pulsating (or rather alternating) with double frequency, has a maximum 45 degrees behind the voltage—a negative maximum, corresponding to power return, 45 degrees ahead of the voltage. Now, you see what happens. As the voltage on the reactive coil lags 60 degrees behind the load, the negative maximum of power in the reactive coil, 45 degrees ahead of its voltage, coincides with the power maximum of the load, which is 15 degrees behind its voltage. Superimposing then the alternating power of the reactive coil on the pulsating power of the load, you get constant power; that is, on the alternator by such a combination you can get constant uniform polyphase load with a single-phase external load, by a reactive coil displaced in phase by 60 degrees, storing energy, and returning it in the single-phase system.

If you look at the distribution of current, you will find that one generator coil carries only the load current, lagging 60 degrees behind the voltage of this coil, or Y voltage; one generator coil carries only the reactance current, also 60 degrees lagging behind the voltage of the coil; and the third coil carries the resultant of the load current, in phase with the coil, and the reactive current, lagging 120 degrees, so combining to a resultant current of 60 degrees lag. In other words, all three coils carry equal currents of equal phase displacements. In short, the machine becomes a perfect polyphase alternator, in armature reaction, in stresses, and in everything, but is storing power during a part of the cycle, to return it into the single-phase system during the other part.

This arrangement may be used occasionally, and may become necessary, if we have to come to the use of very low frequencies.

**W. L. Waters:** Referring to Mr. Steinmetz's comments on my paper on single-phase generators: The system of balancing the load on a single-phase generator advocated by Mr. Steinmetz was, as a matter of fact, the first method which was suggested for overcoming troubles due to heating and loss of efficiency mentioned in my paper. Mr. Steinmetz's scheme is shown in the sketch. Phase *A* of a three-phase generator carries the single-phase load, this load being usually that of a single-phase traction system. Phase *B* carries a choke-coil, which at the full voltage of the machine has a charging current equal to the single-phase rated load of the generator and a power factor of 87 per cent. As Mr. Steinmetz has shown, if the current in the choke-coil *B* is equal to the current on the loaded phase *A*, and if the current in phase *A* has a lag of 30 deg. behind its electromotive force, then the currents in the three phases of the generator will be equal in magnitude and in phase, that is, the load on the generator will be a perfectly balanced three-phase load. That this method of balancing the load on a single-phase generator is only of theoretical interest is at once evident when we consider that the load on such a single-phase generator varies continually, both in magnitude and in power factor. If the choke-coil *B* is adjusted so as to balance the generator when phase *A* carries full load and power factor of 87 per cent, then as soon as the load changes from this value and power factor, the machine becomes unbalanced. If the load falls off to a very low value, then the generator will be as badly unbalanced and will heat just as much as it would if running on full single-phase load without the choke-coil. Thus we can see that even if we use such a choke-coil, we would also require dampers on the pole faces when operating such a machine under the practical conditions of varying load. Such a choke-coil can only be adjusted for one particular value of the current, and can only be adjusted for one power factor—otherwise two choke-coils must be used. Thus we can see that the choke-coil would have little value in practice. It also has numerous disadvantages. As it loads all the phases of the generator, it thus decreases the latter's efficiency and raises its temperature without increasing the output in any way. The cost of such a choke-coil would be substantially equal to the cost of the generator, while the addition of dampers only increases the cost about 10 per cent. We have greater complication, more chance of breakdown, lower efficiency, and an arrangement which is only good for one particular value of the load and power factor. Thus I think it is not difficult to see why this choke-coil method was considered as being of only theoretical interest and as having no practical value compared with the simple, efficient, reliable, and universal method of applying heavy dampers to the field magnets, as described in my paper.

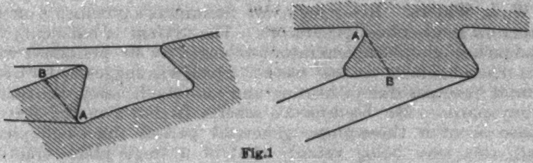

Fig.1

Mr. Behrend, begins by discussing the stresses in rotating disks and rings. The general statements made by him have been well known for the past twenty or thirty years, although there has not been any great necessity to apply them to electrical machinery, as high-speed units are only of comparatively recent date. A large number of approximate formulas have been worked out by various engineers for calculating the stresses in rotating disks and rings, most of them making various assumptions to simplify the problem. The most accurate of these formulas is the one given by Professor Ewing in his treatise on "Elasticity". Mr. Behrend, however, evidently figured his curves given in Fig. 7 from some formula which is only roughly approximate, as they differ 10 or 15 per cent from the stresses given by the most accurate formulas.

The generator described by Mr. Behrend is a 6500-kw., 300-rev. per min., 12,000-volt, 25-cycle, water-wheel driven alternator. The speed of this generator is comparatively high for a large water-wheel driven alternator, but is of very moderate speed compared to steam-turbine driven units, as there are a number of generators of this size operating to-day at 1500 rev. per min., that is, five times the speed of the generator described by Mr. Behrend. We can therefore see that the question of designing such a generator would not mean dealing with any new problems, but would simply mean choosing the design most suitable for this particular unit from a number of existing designs which have been thoroughly tried out. Mr. Behrend omits the electrical design entirely, merely giving us the performance of the machine; but he goes into the mechanical design in detail, and therefore I think we can assume that the latter is considered exceptionally good and that criticism is invited.

The construction adopted is a center disk of forged nickel steel without a hole in the center and with two forged nickel-steel rings, one on either side, and laminated poles dovetailed into the circumference. Before an opinion can be formed as to the suitability of this construction, an idea must be obtained as to the distribution of stresses throughout the field structure. As the stresses figured out considerably too high for conservative practice, the precaution was taken of having them checked before any opinion was formed. Considering first the tangential stresses in the disk, Mr. Behrend's curves give approximately the stresses in a disk of uniform thickness; but taking the disk used in this generator, as shown in Fig. 5, it will be seen that its thickness is by no means uniform. The side rings are registered into, and bolted to, the center disk, evidently in order that the center disk might strengthen the side rings as much as possible, and the result of this design is a disk virtually 32½ in. wide at the circumference and thinned down to 4 in. at the center. We see from Mr. Behrend's curves that even in a disk of uniform thickness the maximum stress in the disk is at

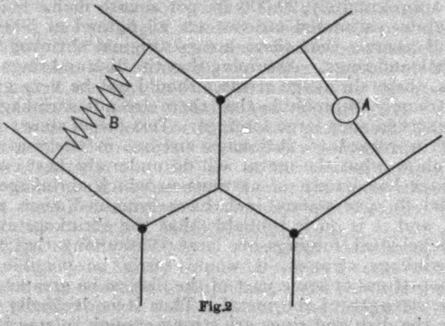

Fig. 2

the center, and in this machine we have 4 inches in the center of the disk carrying the maximum stress due to the 32½-in. rim, and the poles. The stress at the center of the disk at 500 rev. per min. figures out about 35,000 lb. per square inch, which is more than double the stress in the rim. From the drawing we see that the shaft is registered into the disk at the center, and that in order to accomplish this registering the thickness of the disk has been reduced to about one-third, this thinning down being done by approximately right-angle variations in the thickness of the disk. The result of this design is that the stresses as estimated above are by no means uniformly distributed, and will probably run up considerably higher than the estimated 35,000 lb. per square inch around the sharp corners in the disk. It is moderately certain that the center of the disk is stressed in parts above the elastic limit, and that the metal stretches locally to allow other parts of the disk to assist in carrying the stress. The tangential stress in the side rings figures approximately 20,000 lb. per square inch.

The above estimated stresses are all figured at 500 rev. per min. and assume that there are no original shrinkage stresses in the disk and rings. Assuming that the disk and rings are good forgings, these shrinkage stresses should not be very great, but it is extremely improbable that there are not shrinkage strains of some sort in such large forgings. Test pieces show, of course, nothing in regard to shrinkage stresses in the material and merely show what the metal will do under the best conditions. The writer has known of castings in which shrinkage stresses of 25,000 lb. per square inch have remained even after annealing, and it is quite probable that the shrinkage stresses in these nickel-steel forgings are large. Assuming that there are such shrinkage stresses, it would easily be possible for the total hoop stress at some part of the disk to be greater than the ultimate strength of the metal. Thus it is decidedly doubtful whether the disk and rings are strong enough to stand the tangential stresses due to rotation at 500 rev. per min.

Considering next the stresses in the dovetails, the bending stresses tending to break the dovetail across the section *A B* can only be figured approximately. Making the most favorable possible assumptions, the stresses at 500 rev. per min. figure out about 45,000 lb. per square inch at the point *A*. But with a laminated pole and taper wedges, we cannot assume that the stress due to the centrifugal force of the pole is uniformly distributed along the length and width of the dovetail. Also, the overhanging end winding on the pole puts a greater stress on the corner *A* than it does on the center of the dovetail; and the fact that the corner *A* of the dovetail slot in the spider has a comparatively small radius again increases the stress, and may increase it to very high values. If these unfavorable features are neglected, the stress on the dovetail figures out as given above, but taking them into account we find that the stresses may run up to 150,000 lb. or 200,000 lb. per square inch at the same speed. Of course, the exact extent to which these unfavorable features increase the stresses cannot be decided, but it is very probable that the actual stress on the dovetails at 500 rev. per min. is above the ultimate strength of the material. All of this analysis of the stresses assumes, as in the case of the disk and rings, that there are no shrinkage stresses or local flaws in the forging. If there were such bad places, the complete wheel would not be safe even at a lower speed.

It would be difficult to bring the stresses in the dovetails down to a safe working limit; and their intensity in this machine merely confirms the general impression of engineers that the magnet construction, in which complete individual poles are dovetailed into a spider, cannot be used successfully in such large high-speed machines. The difficulty of accurately fitting the dovetails and the difficulty in estimating the exact stresses in them make it necessary to abandon them in favor of some construction which does not possess this disadvantage.

Considering everything, I think it is extremely probable that we would find that the disk and rings had been strained locally above the elastic limit even at the normal speed of 300 rev. per min., and if we were to run the machine at this speed and then shut down and gauge the disc and rings all over we would find that there were evidences of local permanent distortion. Inasmuch as Mr. Behrend has so carefully pointed out that the maximum stresses in the disk are at the center, and since the thickness there could be increased five or six times without any change in overall dimensions, it hardly seems logical to thin down the disk to such a small section.

The design of the 6500-kw. alternator described in Mr. Behrend's paper can hardly be considered as a conservative one or one which it is desirable to duplicate, and I think Mr. Behrend is hardly justified in his statement that the design is " elegant and mechanically superior. "

**Chairman Armstrong:** Mr. Behrend, do you wish to reply to Mr. Waters's remarks?

**B. A. Behrend:** I have nothing to say.

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# DOUBLE-DECK STEAM TURBINE POWER PLANTS

BY J. R. BIBBINS

In the rapid development attending the introduction of the steam turbine, there has been but comparatively little tendency to introduce radical departures from accepted engine practice. The most important changes have taken place in the boiler room, while in the rest of the plant very few changes have been inaugurated other than a general increase of compactness in the turbo-generating room. Outside of the tendency to structural foundations for generating units, there is little opportunity for originality in design without involving a radical change in the ensemble.

There are now in service three important examples of a new type —the double-deck station. This type of station embodies striking originality in its departure from long-established practice, and in a most fortunate manner reserves for the turbine the benefits of certain advantages inherent to this high-speed prime mover. And it is the object of this paper to present in a general way some of the engineering features of this new type of station which, the author believes, deserve careful consideration and ultimate acceptance as standard, at least for power sites of restricted area, as in cities, harbor frontages, hillside locations, etc. No attempt can be made at this time to make more than a cursory study of the important technical points involved, to each of which might properly be devoted an extended investigation.

*The West Point station.* At the outset it will be well briefly to review the most characteristic features of this station before proceeding with a discussion of the double-decked type in general; the features are:

1. Generating machinery above boilers on second floor of station.

2. Weight of generating apparatus supported entirely by steel building skeleton. All footings carried down to the same stratum—rock. 12 in. box columns 33 ft. high.

3. Floor structure continuous, tied in from wall to wall, thus reinforcing over entire structure.

4. Water-cooled floor column passing through middle of boiler setting to reduce weight and cost of beams spanning battery; all other columns straddle boiler setting.

5. Barometric condenser hung from floor girders directly under turbine exhaust nozzle. Designed for moderate vacuum; no air pumps; adjustable cones; centrifugal type circulating pump.

6. Steam piping simple and direct with few bends, draining back from turbine throttle; no superheat; separators in each supply line to turbine.

7. All important steam header and supply lines controlled by pedestal extension valves from turbine floor; non-return valves in delivery from each boiler to prevent back-flow.

8. Header serves largely as equalizer, hence small in size (8 in.); sectioned by valves; operated practically on the unit system.

9. Designed for 200 lb. pressure, high steam velocities; largest steam supply pipe in plant, 8 in., all hung from girders.

10. All auxiliaries steam-driven for feed heating; open type heater; feed taken from condenser hot well.

11. Circulating pumps interconnected for relay working, primed by steam syphons or service pump.

12. Pump suctions submerged 8 ft. in intake bay to avoid surface air; no foot-valves.

13. Two-story side addition accommodating transformers, control and protective apparatus above; heaters and auxiliaries below; also serves as transmission tower.

14. Operating switchboard located in division wall, leaving a clear rectangular operating room, and separate switch room.

15. Generators air-cooled by positive blast piped from outside to reach cooler air and to avoid the possibility of steam from boiler room reaching insulation.

16. Turbine bedplate leveled on plate girders throughout its length with cast lead pad 1 in. thick.

17. Reserve exciter units, steam-driven, exhaust to heater.

18. Transformers mounted on trucks to facilitate replacement by reserve unit provided. See Fig. 4.

19. Ash hoist to be installed from level of ash tunnel to level of siding track.

20. Crane reaches basement through removable section of flooring.

21. Self-supporting, brick lined, steel stack.

22. Flue connections direct to stack; no bends.

23. Elevated tank in turbine room to provide head for gland water and building service.

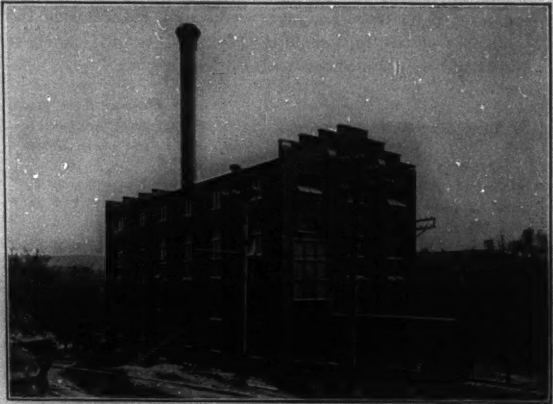


FIG. 1.—Front view, West Point station, switch room extension in rear of building.

The West Point station was designed to serve interurban railway lines through alternating-current sub-stations, and its location is reasonably near the ultimate center of the system. It is but a short distance from some coal mines owned by the company, and the site chosen, at the foot of a hill, permits the use of the impounded waters of two passing streams for condensing purposes. With this site, coal-handling machinery was avoided and barometric condensers used, these several factors combining in the form of the double-deck arrangement.

*Compactness.* As this is perhaps the controlling feature, it is interesting to note that the problem now lies not with the generating, but with the boiler plant. Familiar Corliss engine practice of a decade ago, involving parallel engine and boiler rooms of about equal size, has been superseded by a ratio of one to three, respectively, in turbine plants, unless the boilers be double-decked, as in the large New York plants. It might, then, seem unwise to return to a station arrangement of equal area, as in the two-story building; but it will be found that other advantages accruing in the direction of low cost and simplicity render this arrangement most effective, especially as the extra space on the turbine floor is usually occupied by direct-current converting apparatus serving nearby sections of line.

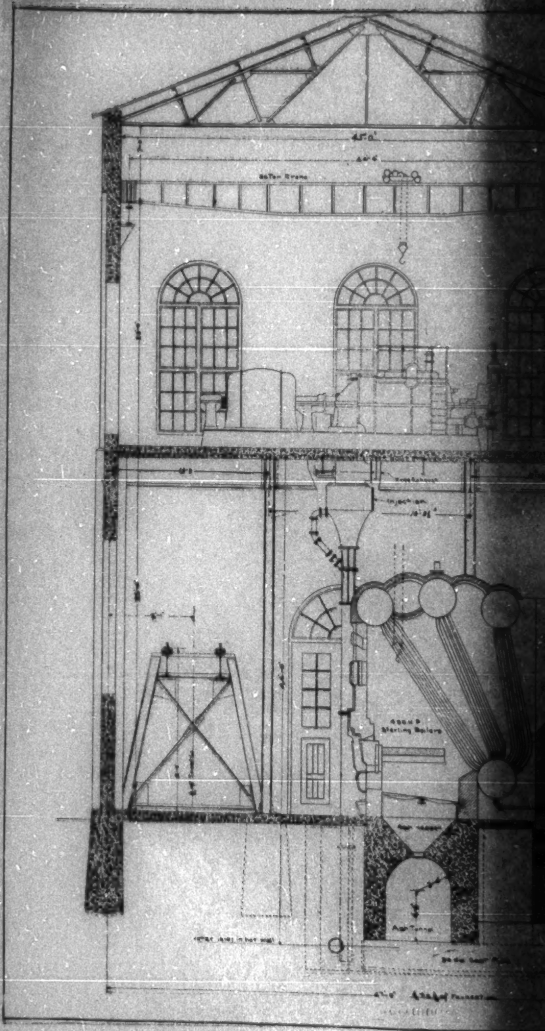
For several years there has been a continual reduction in the bulk and cost of the turbine unit. To what extent, can best be appreciated by comparison with Corliss practice.

| Type of prime mover. | Over-all floor space, square feet per electric horse power. |
|---|---|
| Horizontal Corliss, 500 to 1500 e.h.p. | 0.7 to 1 |
| Vertical Corliss, 1000 to 3500 | 0.35 to 0.4 |
| Horizontal vertical compound Corliss, 7000 | 0.46 |
| Vertical 3-cyl. Corliss, 5000 | 0.2 |
| Single-flow turbine, 1000 to 5000 | 0.17 to 0.75 |
| Double-flow turbine, 15,000 | 0.05 |

Thus, in large sizes, the turbine has reduced floor areas to about 20 per cent. of that required by the modern vertical Corliss engine, and to about 10 per cent. of the horizontal-vertical type. A detailed comparison between single-flow and double-flow types follows:

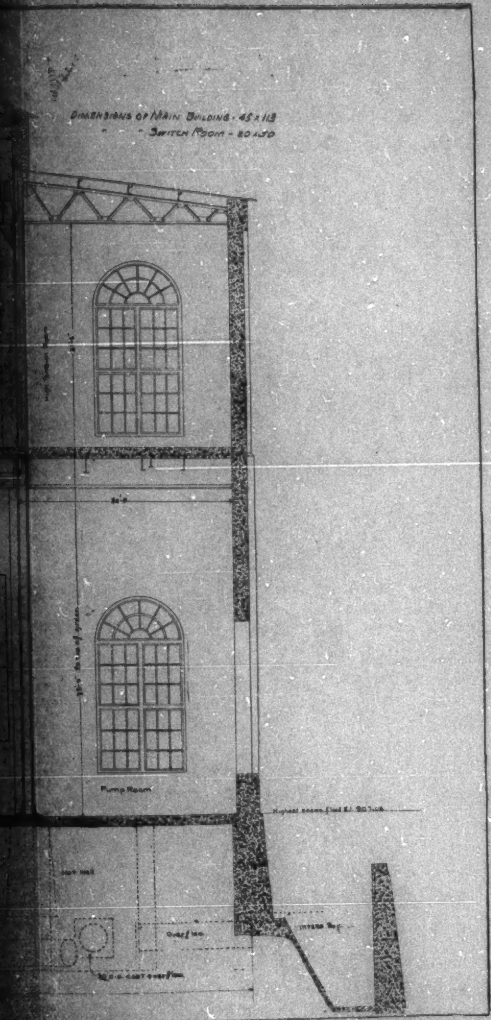
| Unit size. kw. | Type. | Floor space required per sq. ft. per kw. | per e.h.p. |
|---|---|---|---|
| 1000 | Single-flow | 0.200 | 0.149 |
| 1500 | " | 0.165 | 0.123 |
| 2000 | " | 0.141 | 0.105 |
| 3000 | " | 0.101 | 0.075 |
| 5000 | Double-flow | 0.092 | 0.068 |
| 10000 | " | 0.063 | 0.047 |

Similarly in weight per kilowatt capacity. Data are not at hand for comparison with complete reciprocating units, but without generators, large vertical Corliss engines, including flywheel, weigh from 320 to 500 lb. per kilowatt, the weight increasing with the size, whereas the large turbine unit complete


45'-0"
Injection
Stirling Boilers
Ash Tunnel

(Bibbins Double Deck Plant.)

FIG. 2.—Sectional



DIMENSIONS OF MAIN BUILDING - 45 x 113
" " SWITCH ROOM - 20 x 30
Pump Room
Hot Well
Overflow
Intake Bay
cast overflow

Point station.

weighs but a fraction, 15 to 20% of the above, and, moreover, the weight decreases with the size. Considering in addition that the horizontal turbine permits the installation of auxiliaries beneath, this extreme compactness practically eliminates it early in the study of reduced floor area.

The West Point station covers a floor area of two square feet per kilowatt. Considering the small size, this represents a high degree of compactness, relatively better than in some large turbine stations. The Ft. Wayne double-deck station covers 1.42 square feet per kilowatt, ground floor plan, the New York Edison Waterside, No. 2, 0.818, and the Boston Edison 2.64, these latter, twenty to twenty-five times the capacity, and one with double-decked boilers.

Fig. 3.—General view of operating room, West Point.

*Building and foundation construction.* In spite of the relatively high speed, the construction of turbine machinery has been brought to such a state of perfection that structural foundations are permissible in certain types, which at once opens up an extensive field for originality in the arrangement of units and auxiliaries. For example, 1000-kw. units in a power house at Piedmont, W. Va., are supported entirely upon 8-inch cast iron pipe columns with units spaced 10-ft. centers, and all auxiliaries beneath. In a power house in Philadelphia, reinforced concrete posts tied into the concrete floor structure carry the entire weight of the generating plant. As the height of these columns is 20 ft. or more, it is but a step further to employ standard column sections and elevate the machines to a height sufficient to place the boilers beneath. This has been done in the three stations already referred to. At Fort Wayne the turbine floor stands 28.5 ft., and at West Point, 33 ft., above the boiler room on ground floor, by no means an excessive height.

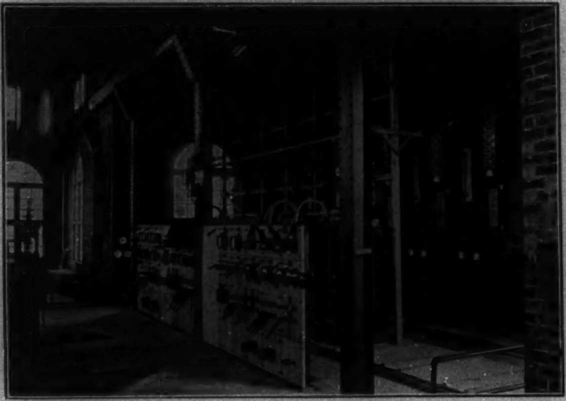


FIG. 4.—Switch room, West Point, showing extension to main operating room.

Here seems to be one of the most advantageous features of the horizontal type turbine—foundation loadings sufficiently distributed to permit of a light foundation structure involving, preferably, but two principal points of support. It might, of course, be possible to provide a supporting column under each of the three bearings; but with the possibility of unequal settling at the footings and temperature changes resulting from the proximity to boiler settings, it is evidently a much simpler solution of the problem to employ two points of support. At West Point only 12-in. box columns are required.

It is, of course, impossible entirely to concentrate the weight of the unit on these columns. A certain proportion must be carried by the building walls. It is therefore desirable to employ a steel skeleton building, carrying the machine crane and roof truss loadings independently of the brick wall. This evidently simplifies to a large degree the problem of maintaining proper turbine alignment. Although strictly necessary only for the turbine supporting structure, the steel work may be extended upward to relieve the wall loading, with little, if any, increase in cost over that of heavier building walls otherwise necessary.

At West Point, the longitudinal members between the turbines are tied together into a *continuous* floor structure from wall to wall, with the sole object of reinforcement, resulting in an exceedingly rigid structure integral with the building skeleton, which has proved to be entirely devoid of any vibration. This applies also to the steel supporting columns which show no evidences of vibration.

*Girder span.* In the double-deck station the problem of relative arrangement of boiler and turbine capacity resolves itself into three important factors: first, number of units required; secondly, boiler grate surface for the required rate of combustion; and thirdly, cost of supporting steel work for different spans. Assuming the first fixed by the necessity of meeting a given station load curve, and the second by standard boiler practice, there remains the problem of restricting girder span over the boiler batteries. With the floor structure designed for uniform loading between supports, the weight and cost of girders will increase approximately with the span, as shown in Fig. 5, plotted for three typical girder sizes.

A rather unusual precedent has been set at West Point, with the object of reducing the dimensions of these cross-members. Instead of a single girder, spanning the entire width of the battery, a row of columns has been located midway. The forward column falls in front of the boiler setting, the rear pierces the setting at the division wall, thus reducing the span to 14 ft. 7 in., and the steel work to 18 in. I-beams. This column must, of course, be artificially cooled. For this purpose, air spaces equal in depth to the column flanges have been provided on both sides, next the furnaces, to permit air circulation from below, and, in addition, cold water is circulated from top to bottom from the building service, with the result that these columns are the coldest in the plant. It is evident that any expansion or contraction would have no effect whatever upon the alignment of the turbine, this occurring midway between the turbine piers. By this unusual expedient, longitudinal girders have been entirely obviated, and the weight of these members reduced theoretically 50 per cent, an appreciable percentage of the whole building structure. In the Ft. Wayne station, 36-in. girders span the boiler batteries with 15-in. I-beams interlacing.

*Boiler duty.* The steam turbine is, of course, admirably adapted to meet the rapidly fluctuating and frequently excessive demands of a high-speed railway system due to a comparatively small number of cars and the universal practice of arranging interurban schedules so that a number of cars start at the same time (the even or the half hour) from important points along the line. This overload capacity of 50 per cent. or more, is readily accomplished by means of secondary admission of steam to the turbine, and fortunately without decreasing its economy to any considerable degree. To meet these fluctuations, a corresponding forcing capacity is required in the boiler plant. Recent investigation and tests have revealed an important fact;

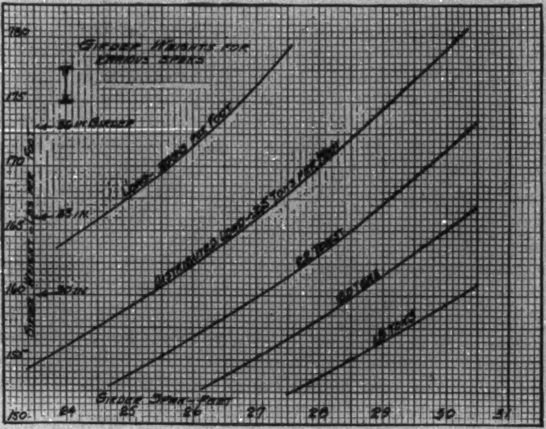


Fig. 5.—Weight of floor girders for different spans and loadings.

viz., that the steam boiler is capable of absorbing heat with very nearly the same efficiency, over a very great range of load. In other words, the boiler itself; that is, the type of heating surface, is a matter of little concern, except in detail proportions and arrangements of baffling, etc. This brings us to the furnace, which involves so many complexities, and upon which such a difference of opinion exists that it would scarcely be prudent to venture an opinion in this brief review of the subject. One thing is certain, however, that in order to avail ourselves of the forcing capacity of steam boilers, a type of furnace must be adopted in which a rate of combustion suited to the work in hand, may be efficiently maintained. For this reason, the mechanical stoker has proved an exceptionally fortunate addition to power plant equipment, insuring a range of generating capacity* far beyond the possibilities of hand-firing.

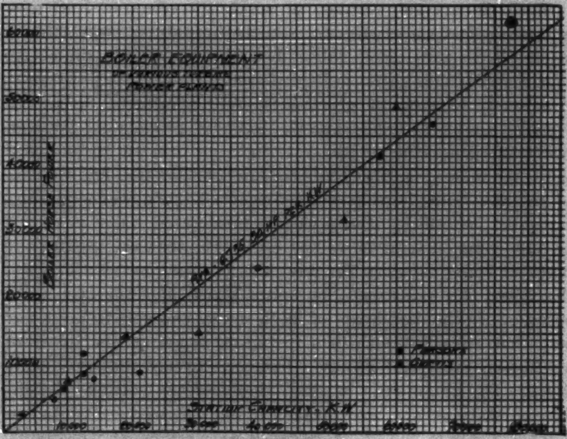


Fig. 6.—Plot representing modern practice in boiler plant equipment.

The high rate of combustion desired has been made possible chiefly by improvements in air distribution, both under the coking arch and in the grate itself. Present indications point to a combustion rate of from 20 to 25 lb. per sq. ft. per hour as a possible normal rating, whereas this formerly stood some 5 lb. lower. This performance involves one fundamental, namely, that the *effective* draft area of the furnace grate should increase with the rate of combustion—a principle quite opposed to increasing the draft pressure *alone* with the rate of combustion in order to obtain the desired quantity of air. The latter is, of course, a fundamental weakness of the hand-fired flat grate furnace, in fact any furnace in which the effective draft area is fixed. Mechanical stoking has its limitations, especially in small plants with cheap labor; but in large plants subject to severe peaks it is often indispensable.

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* See Table No. 1.—Tests conducted upon a standard type water-tube boiler with mechanical stoker fitted with some recent improvements in the form of sectional grate bars designed to promote high rates of combustion. Note that a rate of 46 lb. per sq. ft. per hour (125% overload) was maintained for six hours with less than 0.5 in. furnace draft.

A study of modern practice in the equipment of turbine stations shows a comparatively uniform proportion between boiler and generating capacity. Eighteen modern turbine stations for railway and lighting service average (see Fig. 6) close to one-half boiler horse power per electric horse power generating capacity, including, of course, a considerable boiler reserve.* In this connection, it is well to remember that the greater the range of boiler capacity per unit, the less the reserve necessary, the lower the investment in boiler plant, and the less space occupied. The handicap of high fixed charges to a power plant has already been called to the attention of the Institute by Messrs. Stott and Finlay. Suffice it to say that idle plant should be minimized in the double-deck station design. Several stations are below 0.75 h.p. per kilowatt. Ft. Wayne is 0.57, Yonkers and Port Morris 0.50; Carville at Newcastle, England, is only 0.44, due to liberal economizers.

*Boiler construction*. With one or two exceptions, boiler design has followed along well-established lines. And in the endeavor to keep pace with the great increase in capacity of prime movers, the boiler plant has increased largely in *number*, instead of in *size* of units. But to-day boiler units of 1000 to 2000 h.p. are in active demand. The limitations of the hand-fired furnace have long since been exceeded, and even those of the mechanical stoker in single units. The problem is essentially one of grate surface rather than heating surface; for this reason, the double-fired boiler has come in use. One of this type has already been described by Mr. Finlay. Another is illustrated in Fig. 8, a moderate size unit, employed extensively in a Philadelphia traction station. Quite recently an 1100 h.p. boiler unit of the semi-vertical type has been designed with double stokers and a central combustion chamber of large proportions—a very desirable feature. In the Bow Street station, Charing Cross, London, 1100 h.p. units of an English vertical type and 800 h.p. units of the horizontal type are in operation, the latter with three banks of tubes, superheater between second and third pass. These boilers are fired on three sides with flat grates at a ratio of 65 to 1. Coal is delivered from an overhead bunker to both front and side furnaces and from a point somewhat below the level of the drums, and without exceeding the critical angle, 45°. In the Interborough station, coal reaches both front and rear stokers from a central bin, without incurring an excessive angle to chutes or bends beyond that encountered in any double-deck boiler plant where chutes for the lower boilers must be carried round obstructions.

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* Assuming one boiler out to every nine in operation, this is equivalent to an average evaporation of 22 lb. per kilowatt-hour, including steam for auxiliaries.

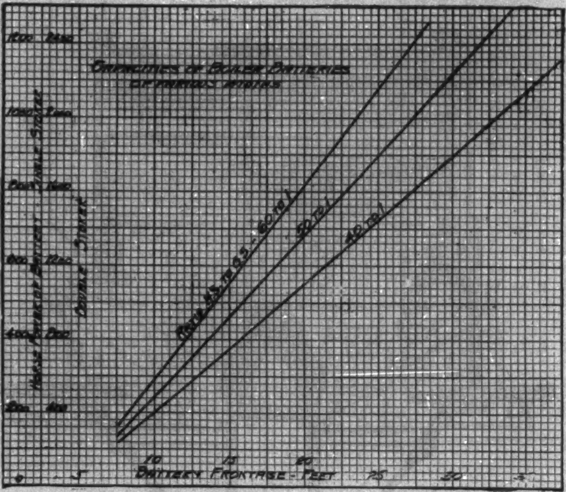

Fig. 7.—Maximum battery capacity for various widths of frontage.

In Table II the general dimensions of a number of large boiler settings are given, together with those at West Point and Ft. Wayne, for comparison. At Ft. Wayne, the stokers are served by an exterior coal bunker running along the face of the building. It is evident that any attempt to apply the double-fired boiler arrangement, would finally reduce to a question of *critical angle* and head room. With the height between floors available in the larger settings, it would seem possible to reach both ends of the boilers from a single side bunker, especially with a boiler setting of moderate depth, such as is shown in Fig. 8. At West Point, the boilers are set farther back than at Ft. Wayne, in order to accommodate a coal trestle forming the storage. But with an external bunker, the settings

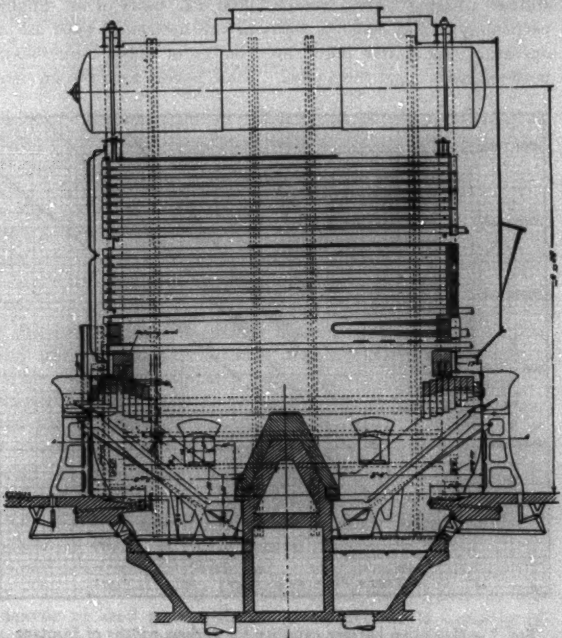

FIG. 8.—Typical setting for large double-fired boiler, 800 h.p., Philadelphia Rapid Transit Co.

### TABLE I.—RESUME OF CAPACITY TESTS

Water-tube boilers; inclined rocking grate stoker; Pittsburg slack coal

| No. of test | 1 | 3 | 4 | 5 | 6 | 8 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|
| Duration, hours | 7 | 6 | 8 | 6 | 7 | 8 | 9 | 9 | 6 |
| Per cent. rating developed | 117.2 | 158.0 | 179.1 | 224.7 | 150.3 | 130.0 | 153.0 | 191.0 | 134.6 |
| Rate of combustion, lb. per sq. ft. per hr. | 23.2 | 28.3 | 38.0 | 46.2 | 27.5 | 22.4 | 27.2 | 37.9 | 23.6 |
| Furnace draft, in. water | 0.14 | 0.27 | 0.295 | 0.424 | 0.24 | 0.21 | 0.31 | 0.30 | 0.22 |
| Evap. lb. per sq. ft. heating temp. per hr. | 4.05 | 5.45 | 6.18 | 7.74 | 5.18 | 4.48 | 5.28 | 6.59 | 4.65 |
| Equiv. evap. (dry coal) lb. | 8.77 | 9.80 | 8.23 | 8.50 | 9.41 | 10.20 | 9.70 | 8.70 | 9.86 |
| Effcy. (dry coal) per cent. | 66.8 | 74.0 | 61.8 | 63.4 | 70.4 | 75.0 | 73.0 | 64.0 | 72.2 |

*Equipment:* Inclined header water tube boiler, 3750 sq. ft. =375 h.p. Ratio heating to grate surface, 49 to 1, natural draft.

### TABLE II.—DATA ON LARGE BOILER SETTINGS

| Name of Boiler and stoker | B. & W. Roney | Parker Roney | Stirling Roney | Hornsby Hand | Hornsby Hand | Stirling Hand | B. & W. Roney |
|---|---|---|---|---|---|---|---|
| Location | Interboro, 59th St., New York | P. R. T. Phila. | Penna. R.R. Harrison, N.J. | Charing Cross London | Charing Cross London | West Point, Ohio | Ft. Wayne, Indiana |
| General type | Horiz. No Sup. | Horiz. Supht. | Vert. Supht. | Vert. Supht. | Horiz. Supht. | Vert. No Supht. | Horiz. Supht. |
| Where fired | Both ends | Both ends | Both ends | Sides and front | Sides and front | Front | Front |
| Boiler h.p. per battery (10 sq. ft.) | 1200 | 1600 | 2200 | 2170 | 1620 | 800 | 800 |
| Ratio grate to heating surface | 30 | 49 | 53.5 | 64.5 | 65 | 50 | 48.3 |
| Area required (sq. ft. per b.h.p.) | 0.56 | 0.363 | 0.352 | 0.464 | 0.445 | 0.59 | 0.69 |
| Frontage of setting at floor | 31 ft. 0 in. | 25 ft. 4 in. | 31 ft. 0 in. | 37 ft. 6 in. | 25 ft. 8 in. | 28 ft. 0 in. | 25 ft. 0 in. |
| Depth of setting at floor | 22 ft. 1 in. | 22 ft. 10 in. | 25 ft. 0 in. | 27 ft. 0 in. | 28 ft. 0 in. | 16 ft. 9 in. | 22 ft. 1 in. |
| Height to center-line of drums | 19 ft. 0 in. | 22 ft. 9 in. | 31 ft. 3 in. | 28 ft. 0 in. | 27 ft. 5 in. | 20 ft. 0 in. | 15 ft. 3 in. |
| Height to top setting | 22 ft. 3 in. | 26 ft. 9 in. | 34 ft. 0 in. | —— | —— | 22 ft. 6 in. | 17 ft. 3 in. |
| Height between floors | —— | —— | 47 ft. 2 in. | —— | —— | 33 ft. 0 in. | 28 ft. 5 in. |

could be located well forward with arches in the building wall communicating with the room under the bunkers. Furthermore, it would seem possible to make use of the space above the coal bunker for a switch room, as it would be approximately at the proper level.* This rearrangement permits of sufficient space in the rear of the boilers for flues overhead and pumps beneath.

In order to indicate in a general way the possibilities of the large boiler units, the author has prepared Fig. 7 showing the maximum stoker grate area that may be installed in batteries of two boilers each, with varying spans between turbine piers, presupposing, of course, that the proper heating surface may be obtained by extending the boiler upward, whether in the vertical type or with an extra bank of horizontal tubes. Thus with a ratio of 50 to 1, a frontage of 30 ft. will accommodate 2240 boiler h.p maximum, sufficient to serve a 3000 kw. turbine. This is approximated in the 2200 h.p. battery noted in Table II, which is 31 ft. over all.

*Condensers*. The West Point station is an excellent example of the possibilities of a compact condensing plant. The barometric condensers are *attached directly to the turbine* exhaust. Here the condensers are arranged in line with the boiler fronts, but with a passage of over 6 ft. between boiler settings, it is quite evident that the condenser may be placed wherever most convenient, irrespective of the position of the batteries, and with a discharge tunnel conveniently located.

It seems almost superfluous to emphasize the advantages of a short and direct connection to the condenser which obviates both the friction of bends and the bulk of large exhaust piping. The suspension at West Point permits of an atmospheric relief connection between the supporting girders, resulting in a distance of only about 2.5 ft. from the floor level to the condenser head. Here the barometric condenser and horizontal turbine are evidently at their best advantage, both as regards compactness and efficiency—an arrangement which cannot be duplicated by any other type of apparatus.

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* In fact boiler fronts might be advanced to the building line, omitting the brick wall entirely from floor to roof, excepting the side wall of the bunker, leaving only the steel columns with a 6-ft. gallery overhanging the turbine room. Switchboards might then be located as at West Point, in line with the steel work, with all control and protective apparatus behind.

The degree of vacuum desirable appears to be a matter of opinion. With a turbine that is not unduly sensitive to vacuum, it would seem unwise to incur the additional complexity of extremely high vacuum apparatus. Indeed, for the majority of inland plants, the high temperature of circulating water available during the summer months would render of no avail the condenser plant designed for higher than 28 in. vacuum. The general preference seems to indicate a moderate vacuum of 27 to 28 in., and several condenser manufacturers are now manufacturing barometric condensers to maintain this vacuum without the use of auxiliary dry air pumps. Taking into account the three or four per cent. gain per inch of vacuum, it is indeed questionable whether it would pay to incur the additional cost and complexity of operation with comparatively cheap coal found in the Middle States. But this is always an individual engineering problem. To give some idea of the limitations of

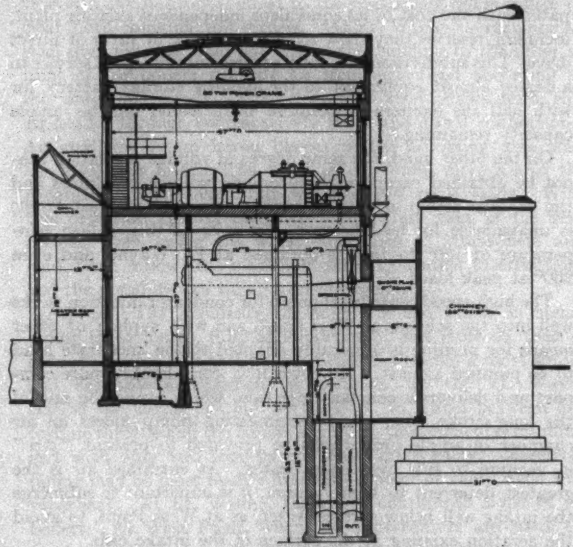

FIG. 9.—Sectional elevation, Ft. Wayne station.

cooling water temperature, it is sufficient to note that with a ratio of 60 of water to 1 of steam, and a condenser working to within 15° of the exhaust temperature, the *maximum possible* vacuum will be 28 in. with 70° and only 27.4 in. with 80° water, not an excessive temperature for midsummer.

*Auxiliary plant.* The Ft. Wayne station employs direct-driven exciters at the end of the turbine shaft, each of sufficient capacity to operate two machines. These direct-connected exciters add 2.6 per cent. to the cost of the main unit, but as compared with the cost of an equivalent independent exciting plant, including reserve, they show some 20 per cent. in favor of direct drive. This subdivision evidently assures uninterrupted service to a degree almost equivalent to the standby storage battery, for with half the exciters inoperative there would still be ample capacity remaining.

On the other hand, the same degree of voltage regulation cannot be obtained except with automatic voltage regulators and the exhaust steam of exciters such as are used at West Point, is unavailable for feed heating. In spite of this, a feed temperature of 160° to 180° is obtained at Ft. Wayne and even 200° at peak loads.

The high-speed centrifugal pump for condenser injection works well into the scheme at West Point, and with syphon or other means for priming is admirably adapted to the moderate head to be pumped against. Moreover it is considerably more compact and delivers a constant injection, which cannot be said of the long stroke, slow-speed reciprocating pump unless an air chamber of ample proportions be provided to prevent "dip" in vacuum to tide over dead center. As entrained air is the greatest deterrent to high vacuum, it is important to submerge the intake well below surface water, as at West Point, to avoid the aeration existing at the surface of the intake crib.

The question of auxiliary drive is important. Recently it developed during a test that a 1000 kw., well equipped turbine station was using on the average nearly 24 per cent. of the total steam in auxiliaries. A common figure is 10 to 12 per cent. for plants of 1000 to 2000 kw. Hence the necessity of moderately economical auxiliaries. At one turbine station in Philadelphia the condenser discharge pump is driven by a belt from the turbine shaft. This, however, would not be applicable in the double-deck station. At Newcastle, England, all auxiliaries are motor-driven, economizers being used to heat the feed water. It is evidently a nice engineering problem to find a happy medium between excessively wasteful auxiliaries, and low feed temperatures.

*Ventilation.* In the double-deck station it is important to draw ventilating air from the outside to avoid not only the heat above the boilers, but also the possibility of escaping steam reaching the generator insulation. Some little difficulty here arises in avoiding structural work, but hardly to any greater degree than in the ordinary station. At West Point, one vertical and one horizontal offset to the ventilating ducts suffice to clear both columns and girders. At Ft. Wayne, a rectangular steel duct extends from one end of the building to the other in front of the boilers, drawing air from either end, according to the prevailing winds. Each generator then draws from this air header through comparatively short and direct connections. An auxiliary steam-driven blower in the adjoining area way has also been installed to assist in delivering more air to the generators during very hot weather and peak loads. With this provision against excessive temperature rises in the generators, even under the worst conditions of atmosphere and load, there follows the maximum security against interruptions and the possibility of tiding over emergencies.

*Piping.* The avoidance of long runs and bends in steam piping is, of course, fully as important, if not more so, than in exhaust piping, and with boilers beneath turbines a most simple and desirable arrangement is possible. In the Ft. Wayne station the steam has but 30 to 35 ft. to travel between any turbine throttle and the boilers supplying this particular machine, and with only two long-sweep bends intervening. Moreover, piping may be most readily drained—a point of value, even with superheat. At Ft. Wayne, there is a continuous slope to the boilers. At West Point, where no superheaters are used, the header is drained by steam traps, separators being provided in each turbine line as an additional precaution.

Under normal working conditions, therefore, the plant operates almost entirely on the *unit system*, with the interconnected header properly sectioned to isolate trouble in emergencies. In both stations each turbine line connects to the header close to the feeders from the boilers supplying it, so that the header operates simply as an equalizer between the various points of demand. Owing to the directness of the piping, comparatively high steam velocities and small pipe sizes may be employed, thus reducing radiation without serious drop in pressure. The great simplicity of this piping arrangement is well attested by the fact that at Ft. Wayne the cost, complete, from boiler nozzle to turbine throttle, was only $2.50 per kilowatt.

*Switch room.* There is an excellent building arrangement at West Point to provide for switch room and auxiliaries. An addition to the rear of the main building accommodates the electrical apparatus above, and the feed pumps, circulating pumps, and heater below. This addition leaves a rectangular engine and boiler room of minimum proportions, with centralized auxiliary and electrical control plants, permitting the installation of the switchboard in a most convenient position between the building columns, with all the high-tension apparatus in the rear, including high-tension bus-bars, circuit-breakers, and protective apparatus with transmission line outlets near the roof. In the 33 ft. between floors, there is space for a mezzanine floor or gallery for some of the small auxiliaries, but this has not been made use of at West Point. To be sure an elevated switchboard might have been used as at Ft. Wayne, but the extra room required for heaters and auxiliaries, would

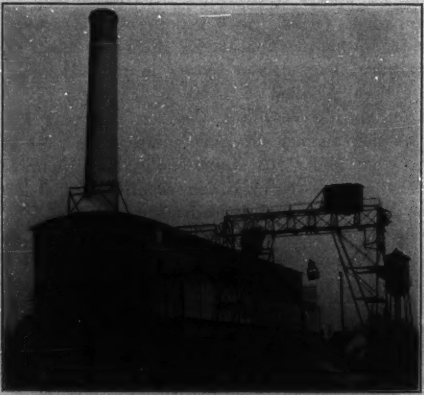

FIG. 10.—Ft. Wayne station, showing coil handling and storage arrangements.

necessarily have been provided in the main building at the cost of extra ground floor space.

*Summary.* We have touched briefly upon certain features of the double-deck type power station, which constitutes the most important factors in working out a successful design. Inasmuch as many of the refinements of modern power stations are absent, the highest operating efficiency could scarcely be looked for, and in the three stations already built *simplicity* has perhaps been the controlling factor, leading to minimum labor cost. On the other hand, non-indulgence in refinement has greatly reduced the first cost of the complete station. Incidentally, lower fixed charges are incurred against operation, also a somewhat lower rate of depreciation. The general result is a tendency to make the total cost of operation lower than in a more efficient plant with correspondingly high investment.

The Ft. Wayne station is an excellent example of this principle. Based upon the present cost, the power station when completed—8500 kw. in capacity—will have cost $66.25 per kw. exclusive of all sub-station apparatus, property, and siding. For the present uncompleted plant, the cost per kilowatt is, of course, higher—around $75 per kilowatt, including sub-station

TABLE III.

COST OF COMPLETED POWER STATION, 8500 KW., NO SUB-STATION APPARATUS.

| | $ | $ per kw. |
|---|---|---|
| *Building*: Including general concrete and steel work, coal bunker, smoke flue, condenser pit, coal storage pit, etc | 93,217 | 10.97 |
| *Generating plant*: Including turbines, generators, exciters, cables, switchboards, transformers, and ventilating ducts | 259,711 | 30.55 |
| *Boiler plant*: Including boilers, superheaters, stokers. piping, pumps, heaters, settings, breechings, and tank | 118,313 | 13.92 |
| *Condenser plant*: Including condensers, pumps, piping, free exhausts, water tunnels, and intake screen | 33,790 | 3.98 |
| *Coal handling plant*: Including gantry crane, crusher motors and track | 7,990 | 0.94 |
| *Erection*, superintendence and engineering | 50,500 | 5.94 |
| Total, excluding property and siding | 563,520 | 66.25 |

equipment. To show the distributed cost, Table III is quoted from a former paper. To many, these costs will appear exceptionally low, but they are correct as far as it is possible to segregate the various items from the numerous vouchers. This at least will serve to show the tendency toward low station costs, resulting from simplicity of design. In smaller stations, like that at West Point, such low cost would not, of course, be expected; in larger ones it should be even lower.

The price of coal and labor is in all cases a controling factor. With cheap coal, high vacuum and superheat, high-efficiency auxiliaries and economizers are evidently non-essential. But with coal above $3.00, and with city labor, conditions might at least justify the use of superheaters, and amplified condensing plant, with rotative dry-air pumps. The internal type superheater is now a simple and durable apparatus for moderate temperatures when protected by sufficient steaming surface; that is, installed between first and second pass of tubes. There is at present a tendency in boiler practice toward the addition of so-called economizer surface to the boilers themselves, rather than in the form of external economizers.

For the average power plant, the more moderate conditions of operation appear to be in favor—150 to 175 lb. pressure, 75° to 125° superheat, and 27 to 28 in. vacuum. The examples we have studied show that an extremely simple plant design embodying these features, is possible. That future development will result in still further improvement, goes without saying. Much credit is due the designers of these present stations for their courage and initiative in testing out the possibilities of the double-deck type.

## Discussion on "Double-Deck Steam Turbine Power Plants." Atlantic City, N. J., July 1, 1908

**C. W. Ricker:** The additional data which I have to present should properly have been included in Mr. Bibbins' paper, but as an analysis of all the vouchers had to be made to determine these data, which could not be done in time, they will be offered as discussion as briefly as possible. The data are as follows:

Youngstown & Ohio R. R.R.—West Point Power Station
Analysis of Cost of Completed Plant, 3000 kw.

| *Building and fixtures,* | *Cost* | *Per kw.* |
|---|---|---|
| Foundation, general excavation, and concrete work including condenser wells and overflows and ash tunnel; steel frame and building superstructure, ash-handling apparatus, coal trestle, chimney, smoke flue, and crane | $64,204 | $21.40 |
| *Boiler plant,* | | |
| Six 400 h.p., No. 200 water-tube boilers, settings, furnaces, pumps, heater, piping and covering | 42,726 | 14.24 |
| *Condenser plant,* | | |
| Three barometric ejector-type condensers with separate centrifugal pumps, water intake and dam including deepening channels | 19,224 | 6.41 |
| *Generating plant,* | | |
| Three 1000-kw., three-phase, 25-cycle, 400-volt turbo-generators. Six 375-kw., 22,000-volt step-up transformers, duplicate exciters, switching, and protective apparatus | 112,764 | 37.59 |
| *General expense,* | | |
| This includes items not susceptible of distribution and part of the expense of supervision | 7,252 | 2.42 |
| Complete | $246,170 | $82.06 |
| Sub-Station equipment in power station. | | |
| Two 300-kw. synchronous converters with five-panel switchboard | 12,600 | 4.20 |
| Total | $258,770 | $86.26 |

This, of course, is a comparatively small station and the items of general character, mainly in the building and fixtures, are necessarily larger in proportion than they would be in a station of greater capacity. These costs were also increased materially by the position of the station, which is some seven miles from the nearest steam railroad station at which freight could be received. The entire building frame and steel work, and all of the cement and sand used in the foundation and water and ash tunnels, and the machinery and tools used in preparing and erecting these items, had to be hauled over seven miles of bad country roads with steep grades at an expense of from $2 to $4 per ton, which amounts to a considerable item.

The station building has a complete steel frame, which was erected on the foundations, before the brick work was begun. The accompanying photograph shows the completed frame.

To show the steadiness of the station, a photograph was taken by the Cooper-Hewitt lamps used for general lighting.

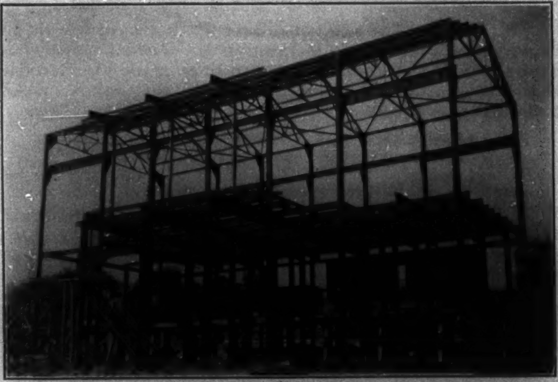

FIG. 1—West Point power station steel frame.

FIG. 2—West Point power station from top of crane.

A portable box camera mounted on a light tripod was set up on top of the crane, which is about 33 ft. above the station floor, in a position to experience the maximum vibration. A two-minute exposure was taken, and a perfectly sharp, clear picture resulted, which seems to show a degree of steadiness at least entirely sufficient for operating requirements.

**J. R. Bibbins:** I am exceedingly gratified in Mr. Ricker's presentation of the cost of the West Point station. The total figure he has quoted, approximately $82 per kilowatt for the plant complete, corroborates the figures noted in the paper for the cost of the Ft. Wayne station complete, $66.25 per kilowatt. Considering the largely increased expense in transporting erecting and building materials to a comparatively inaccessible location, it is safe to say that a station of this kind could be duplicated in a city like Ft. Wayne for even lower cost. For a complete power station of high-grade construction throughout and only 3000 kw. capacity to total as low as $82 per kw., emphasizes the principal theme in this study of power station construction. With these two excellent examples before us, the double-decked type station should, in future station work, evidently receive the thoughtful consideration of every power plant designer.

This type is applicable not only to the turbine, but also to producer gas plants of considerable capacity where the relative location of power machinery may be reversed to good advantage —the engines upon the ground floor and producers, scrubbers, and all auxiliaries on the second floor. Recently a 16,000-kw. plant was designed for a large city railway system, in which the ground floor area was only 2.25 sq. ft. per kilowatt, accommodating eight 2000 kw., tandem, horizontal gas-engine units and 24,000 h.p. in producers, all in a building 336 ft. long, 107 ft. wide and 82 ft. high, to the lower chords of the roof trusses. In this type of plant the building structure is comparatively light by reason of exclusively static loading and the absence of extremely heavy parts in producer-gas apparatus.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 1, 1908.*

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# WORKING RESULTS, GAS-ELECTRIC POWER PLANT

## REPORT OF 30-DAY TEST ON SERVICE PLANT, RICHMOND WORKS AMERICAN LOCOMOTIVE CO., RICHMOND, VA.

BY J. R. BIBBINS

In this paper an attempt is made to present a general study of a problem upon which only very limited data seem to be available—power generation by gas-engine-driven plants, its commercial efficiency, and ultimate cost. It seems best to approach the subject from the operating standpoint, basing calculations upon actual working results from a specific case, one of demonstrated fact. The Richmond tests* are conclusive in this respect, and although somewhat limited in scope (being only a commercial test), nevertheless provide a starting point for further deductions. While of a somewhat cursory nature, it is hoped the data presented will serve at least to emphasize the wide field of the modern gas power plant.

*The Richmond plant.* The equipment consists of a 23.5 by 33 in. horizontal, tandem gas engine, with a direct connected direct-current generator, operating on producer gas generated by a pair of 9-ft. (shells) bituminous producers. The gas is purified by means of wooden slat scrubbers and centrifugal tar extractor, motor-driven. A 15,000 cu. ft. holder serves to equalize its quality and to start the engine, which is necessary to bring the motor-driven auxiliaries into service. The engine is of the modern double-acting type, giving two impulses per revolution, and is governed by a sensitive oil relay system designed to relieve the governor of all valve work. Employing the *constant qual-*

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* Presented by courtesy of Mr. Wm. Dalton, chief engineer, American Locomotive Co.

*ity* method, the ratio of air to gas is constant except when the gas itself changes, for which event hand-regulating dampers are provided. Duplicate igniters work together for increased security. For the same reason duplicate sources of igniter current are available—motor-generator and lighting mains. An important feature of the producer is that it is designed for continuous operation, having a water-sealed bottom instead of a closed ash pit, to permit the removal of ash at any time. It generates its own steam, requiring no auxiliary boilers, so that the only auxiliaries required for the entire plant are a motor-driven fan, tar-extractor, and igniter set. In the aggregate these auxiliaries absorb about 5 per cent. of the station capacity.

The Richmond works employ motor-drives to a considerable extent, and for such diversified purposes that the individual demands superpose to a large degree and yield a fairly constant total. This is a condition conducive to the most efficient working of a gas power plant, and influenced to some extent the choice of this form of motive power in this particular location. Constituting the main service plant of the Richmond works, it is called upon for continuous 24-hour service, except on Sundays and holidays.

Herein lies one essential requirement for a producer plant test. Owing to the comparatively long period required for a pound of fresh coal to work through a fuel bed several feet deep, a long test is necessary for any degree of accuracy. With the rapid combustion on a boiler grate, this is a different matter, and an 8- or 10-hour test will suffice. But in producer work, 24 hours, or 48 hours, is the minimum. In this case, the test was continued for practically four weeks, half of the time on a full load run and the remaining two weeks to three-fourths and one-half load respectively, with a rate of gasification of 0.25 tons per hour. A continuous run of 223 hours' duration evidently provides an excellent guarantee of accurate results.

*The test.* From the great mass of data recorded during this test, it will suffice to extract only such as pertain to the operation of a plant of this nature. The test was conducted entirely by the company's engineering and operating staff, and for the purpose of determining the fulfilment of guarantees. The electrical output was measured by direct-current recording wattmeters calibrated from a laboratory standard previous to the test. The water consumption was also metered, no great accuracy being desired. The coal was weighed by scales checked from time to time by standard weights.

Samples from such weighings, accumulated during a day's run, were quartered down and sealed for analysis, Table I.

It should be noted that at full load, 312 kw., the engine was running somewhat below full rating, but the true full-load coal consumption may readily be found. For this purpose, these data have been plotted in Fig. 1 in the form of three related curves: (a) Rate of gasification in pounds per hour; (b) Pounds per unit of output per hour, and (c) Corresponding thermal efficiency. The first mentioned curve is important in all analyses of steam or gas engines to determine the rationality of the results, for the line of heat input to the engine as well as to the producer should be practically straight, as developed during the test of a similar engine at the works of The Norton Company.* The second curve, showing the relative fuel

TABLE I.

General Results of Test.

| Nominal Load | Full | Three-Quarters | One-Half |
|---|---|---|---|
| Length of run, hours | 223 | 125 | 136 |
| Average load, kw | 312.3 | 228.3 | 159.6 |
| Average load, computed brake h.p | 455.0 | 333.0 | 238.0 |
| Load, per cent. engine rating | 91.0 | 67.6 | 47.5 |
| Load, per cent. generator rating | 104.0 | 77.2 | 53.2 |
| Coal gasified, lbs | 115,289 | 54,143 | 47,775 |
| Coal gasified per hr | 517.0 | 433.0 | 351.0 |
| Output, kw-hr | 69,650 | 28,540 | 21,710 |
| Lbs. coal per kw-hr | 1.654 | 1.697 | 2.20 |
| Lbs. coal per kw-hr., guaranteed | 1.93 | 2.10 | 2.64 |
| Lbs. coal per brake h.p-hr | 1.14 | 1.31 | 1.56 |
| Avg. heat value of coal, B.t.u | 14,392 | 14,392 | 14,392 |
| B.t.u. per kw-hr | 23,700 | 27,280 | 31,650 |
| B.t.u. per brake h.p-hr | 16,415 | 18,710 | 21,670 |
| Per cent. thermal efficiency, brake | 15.51 | 13.6 | 11.75 |
| Per cent. thermal efficiency, elec | 14.35 | 12.65 | 10.78 |

*Coal.*—Pocohontas run-of-mine; avg. heat value dry sample, 14,703, as fired, 14,392; volatile matter, 22.8%, ash 4.5%, sulphur 1%.

*Test.*—August 12, 7 a.m., to September 7, 12 m.

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* Transactions A. S. M. E., December, 1907.

economy at variable loads, necessarily follows the form of an equilateral hyperbola, being derived from the line of total coal input. Finally, the third curve, efficiency, represents that part of the heat in the coal that has been converted into useful work. This is absolute or kinetic efficiency, and not akin to the "efficiency ratio" employed in steam-engine practice. It covers all losses between coal pile and switchboard.† From the curve, Fig. 1, the gross coal consumption of the plant at full engine load, is 550 lb. per hr., or 1.59 lb. per kw-hr., equivalent to approximately 1.09 lb. per brake h.p-hr. And with 400-kw. load, which is easily within the limits of this particular plant, the coal consumption would be roughly 1.5 lb. per kw-hr., or 1.0 per brake h.p-hr.

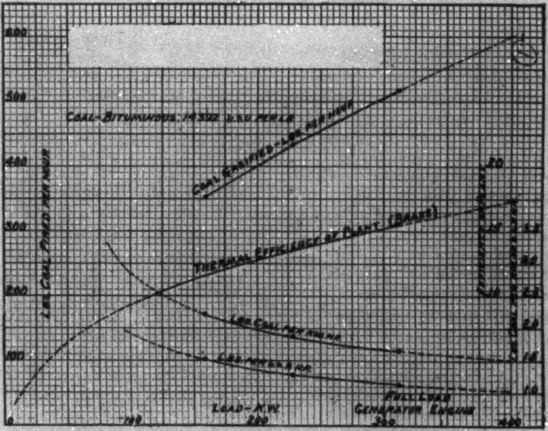

FIG. 1.—Gas power plant economy at various loads.

This characteristic of constantly increasing economy shown by the gas engine plant up to the point of maximum load illustrates an essential difference from steam engine economy which usually is best at loads 70 to 80 per cent. rating, according to the cylinder ratios employed. Although the gas economy curve is quite flat beyond half-load, yet the plant evidently does its best work well loaded. By projecting backward the line of total coal gasified, we find that it requires over one-third of the full-load coal to run the plant unloaded. This represents a standing charge against its operation, becoming less and less important as the load increases. Barring this constant loss, this plant would be capable of generating power at the rate of one pound of coal per kilowatt-hour, which rate would, moreover, be *constant at all loads.* In other words, additional load might be acquired at this rate by providing for the constant losses as a fixed charge. This method is actually employed by some central stations in determining power rates.

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† Taking the mechanical equivalent of heat as 776 B.t.u., the thermal value of one horse power is 2545 B.t.u., or of a kilowatt, 3412 B.t.u. Hence, absolute thermal efficiency = 2545 ÷ B.t.u. per b.h.p., per hour, or upon an electrical basis, 3412 ÷ B.t.u. per kw-hr.

During the four weeks' test, there were several days during which the plant was allowed to stand idle, as the works are not operated Sundays. During this period, some coal was required to keep the producer fires at their normal level and in good condition. It would, of course, have been possible to starve the fires during standby periods, but this would simply have resulted in a higher coal consumption during the succeeding run. According to the judgment of the producer operator, an average of 1700 lb. of coal were required to compensate for standby losses from 6 p.m. Saturday until 7 a.m. Monday, a period of 37 hours. Herein lies a remarkable feature of the producer plant—the low rate of standby losses, averaging only 46 lb. per hour, or 2.5 per cent. of the weekly coal consumption.

Carrying this analysis one step further, Fig. 2 shows a graphical method of determining the producer plant efficiency. Here are plotted three economy tests and the standby loss. Not knowing the heat input to the engine at various loads by actual test, the guaranteed efficiencies have been plotted extending the line backward to a point of zero input. This corresponds to 166 kw. total losses in the engine unit. Assuming that the producer is maintained ready for operation, there are four points to determine the curve or line of producer input. And the ratio between engine and plant input gives directly the gross efficiency of the gas generating plant from coal pile to engine throttle. This curve shows that the producer maintains remarkably uniform efficiency throughout the range of plant load. This results from the fact that at zero output of station the producer is operating at over one-third its full-load rate.

A careful measure of oil consumption was made during the two weeks' run at full load, comprising 223 hours' operation, also the water consumption of the engine. During this period, the average rate of cylinder oil consumption was 0.09 gal. per hour, or, on the basis of a ten-hour working day, 4.9 gal. per week. This confirms to a considerable degree, the experience at the Norton works, where an engine of the same size uses 3.5 to 4 gal. per week, ten-hour day—a rate so low as to have excited suspicion of its correctness. The high economy of oil is, however, due to the system of timed, forced circulation employed.

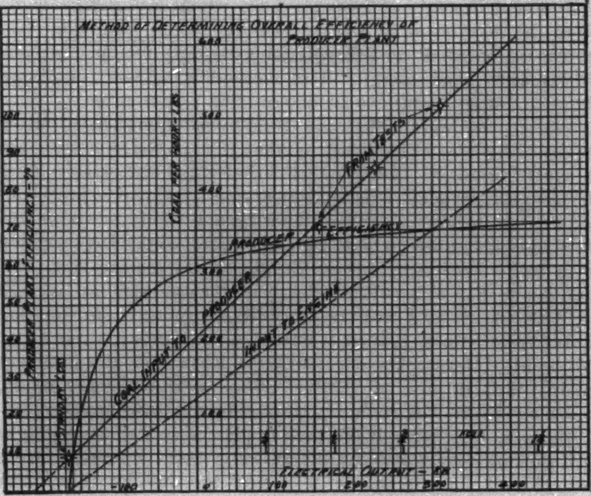
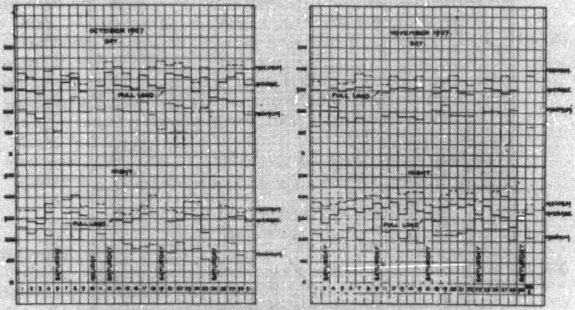


FIG. 2.—Graphical method of determining over-all efficiency of producer plant.

The average quantity of cooling water used was 6.56 gal. per boiler h.p-hr. at heavy load with inlet temperature varying from 75 to 80° fahr. and outlet from 140 to 150° fahr. This quantity is quite reasonable for the temperature rise. Inasmuch as a definite quantity of heat must be removed from the engine at a given load, the volume of water necessary evidently varies with the rise, so that in winter even less cooling water would be required. Economy of water may be carried to any reasonable point provided the outlet temperature of any part does not exceed 150° fahr. The upper limit only is important.

*Operating results.* It seems to be the general impression that a gas-power plant must be handled gingerly in order to obtain good results. The accompanying operating data from Richmond should dispel this impression. Fig. 3 shows typical results for two months' operation, representing, if anything, an output somewhat below normal. It is worth while to note the continuous operation throughout the week, 24 hours per day, and particularly the high average load sustained. The normal run at Richmond is six days without stopping. In fact the producer fires remained undisturbed from July 4, 1907, until early in the present year, when an opportunity occurred to make careful inspection of the entire equipment.



TYPICAL MONTHLY LOG - 500 HP - 300 K.W PRODUCER PLANT SHOWING AVERAGE, MAXIMUM AND MINIMUM LOADS RECORDED EACH DAY.

FIG. 3.—Electrical log for two months, showing average maximum and minimum loads carried.

The plant has sustained a load of 410 kw. for three hours, 19 per cent. overload on the engines, and even higher overloads for short periods. With rich gas, the power of the engine is correspondingly increased in a manner exactly analogous to the effect of variation in boiler pressure in a steam plant. How far this conservative practice may be carried depends upon the operator; it is for him to decide the limitations of his plant.

*Operating costs.* From the preceding data and the other items of cost, the cost of power may be estimated at various load-factors. Owing to the fact that the present power plant was

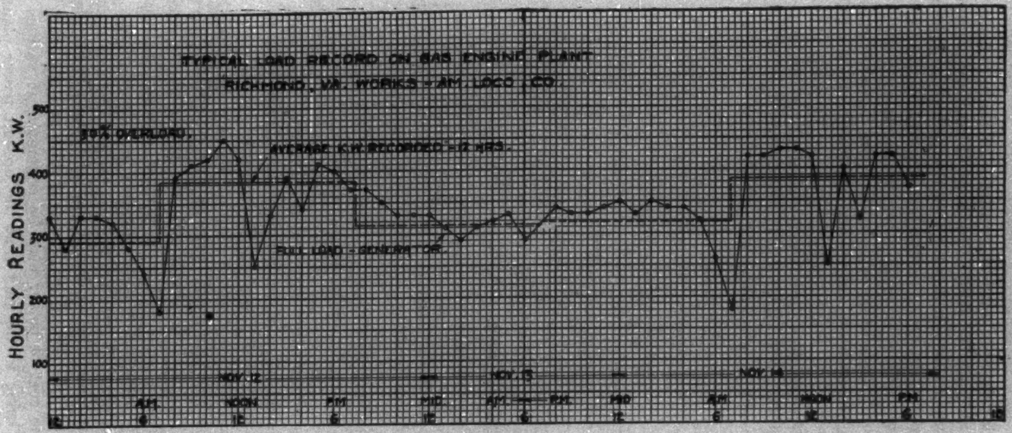


FIG. 3A.—Typical hourly load record, showing overload capacity of plant.

made to accommodate a two-unit plant, the cost has been computed upon this basis; and in view of the excellent results that have been obtained the electrical rating of the plant has been placed at 700 kw., or 1000 h.p., at which rating the investment cost becomes about $138 per kw., or $96 per brake h.p. complete, including machinery, buildings, foundations, piping, erection—in fact all items except the value of the land occupied. Considering the limited size of the plant, this does not represent an excessive cost, which in large plants would probably be as low as $100 to $125 per kw.

### TABLE II.

### Cost of Power, 700 kw. Gas Power Plant.

### Assumptions.

| | |
|---|---|
| *Equipment cost*: | |
| Building and machinery | $96,600 |
| Cost per kilowatt, $138, per brake h.p., $96.60. | |
| *Fixed charges*: | |
| Interest 5%, taxes and insurance 1.5%, depreciation (sinking fund 15 years 5%), 4.63%, running repairs 1.5% on investment. Total 12.63% per year | 12,220 |
| *Operation*: | |
| 300 days, 7200 hr. per year, 5,040,000 kw-hr. | |
| Input to auxiliaries, 5.4% full, 10.8% half-load. | |
| Standby losses, producer plant, 1600 lb. per week, 2.1% full, 3.1% half-load. | |
| Fuel rate, full load, 1.59 lb. + 2.1% = 1.62 lb. per kw-hr.; ½-load 2.1 lb. + 3.1% = 2.17 lb. per kw-hr. | |

### Cost of Power, 700-kw. Turbine Plant.

### Assumptions.

| | |
|---|---|
| *Equipment*: | |
| Building and machinery, $100 per kilowatt | $70,000 |
| *Fixed charges*: | |
| Interest 5%, taxes and insurance 1.5%; depreciation (sinking fund 16⅔ yrs. at 5%) 4%; repairs 1%; total 11.5% | 8,050 |
| *Operation*: | |
| 300-day year, 7200 hr. | |
| Average water rate, full-load 21.5 lb. per kw-hr. | |
| Average water rate, one-half load 25.5 lb. per kw-hr. | |
| Gross evaporation, 7.5 to 8.0 lb. | |
| Standby, banking, 10 to 15%. | |
| Gross coal consumption, full, 2.96 lb. per kw-hr.; half, 3.9 lb. per kw-hr. | |
| *Wages and supplies*—Same as gas. | |

In this total cost of power are included the usual fixed charges—interest at 5 per cent., taxes and insurance 1.5 per cent. In the absence of any data on repairs (there having been none on the engine up to the present time, and very small repairs on generator and producer), this item has for convenience been included in the fixed charges at 1.5 per cent. on the plant investment. Further, depreciation has been included in the form of a *sinking fund,* based upon 15 years' life of plant at 5 per cent. interest. This latter method may be contrary to general practice, but considering the nature of the depreciation fund and its earning capacity, the annuity method seems most logical.

TABLE III.

Cost per Kilowatt-Hour and Horse-Power-Year, Gas Plant.

| Cost items | | Full load | Half load |
|---|---|---|---|
| | | Cents per kw-hr. | |
| *Coal* | at $1.00 | 0.081 | 0.109 |
| | 2.00 | 0.162 | 0.217 |
| | 4.00 | 0.324 | 0.434 |
| | 6.00 | 0.486 | 0.651 |
| *Wages* | per year, $6,160 | 0.121 | 0.242 |
| *Supplies* | " 3,850 | 0.076 | 0.143 |
| *Fixed charges* | " 12,200 | 0.242 | 0.484 |
| *Total costs*—coal at $1.00 | | 0.520 | 0.978 |
| 2.00 | | 0.601 | 1.086 |
| Richmond coal....2.70 | | 0.658 | 1.163 |
| 4.00 | | 0.763 | 1.303 |
| 6.00 | | 0.925 | 1.520 |
| | | Dollars per electric h.p. year | |
| *Equivalent power rate*: | | | |
| 300-day year, coal at $1.00 | | $27.90 | $52.40 |
| 2.00 | | 32.30 | 58.20 |
| 2.70 | | 35.60 | 62.40 |
| 4.00 | | 41.00 | 69.90 |
| 6.00 | | 49.60 | 81.50 |
| Charges for auxiliaries if motor-driven | | 2.7% | 7.4% |
| *Saving gas over steam*: | | | |
| Coal at | 1.00 | —3% loss | —8.5% loss |
| | 2.00 | +8% gain | +0.9% gain |
| | 2.70 | 12.9% " | 4.7% " |
| | 4.00 | 19.6% " | 12.4% " |
| | 6.00 | 33.7% " | 19.0% " |

These costs are shown in Table III. Based on 300-day operation, 7200 hours per year, the fixed costs are distributed only over the operating period, not over the entire year. And, assuming the price of coal largely determined by location, the efficiencies at various loads are considered constant, irrespective of the price of coal. Both standby losses and power consumption charges have been included. As we are considering an industrial plant in which the load averages practically uniform throughout the day, it suffices to estimate power costs at full and half loads respectively. This has been done in Table III for various coal prices. Coal prices are based upon net ton.

The results show that at the price of fuel at Richmond, $2.70, power can be delivered at switchboard at a cost of two-thirds of a cent per kilowatt-hour for a fully loaded plant operating 7200 hours per year, or less than 1.25 cents operating at half-load, and this taking into account fixed charges which range around 40 per cent. of the total cost. Even with coal as high as $6 per ton, the total cost of power would be under one cent per kilowatt-hour, obviously an excellent result.

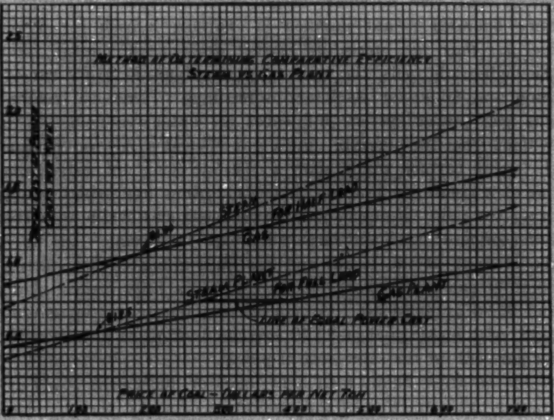


Fig. 4.—Graphical method of determining comparative cost efficiency producer gas versus steam turbine plant for Richmond conditions.

*Relative cost of gas and steam power.* That there may be no misunderstanding of the preceding cost results, a comparison has been drawn up for a steam turbine plant operating under the same load. This comparison covers only two variable factors, coal cost and loading. And, while not intended to be of more than tentative interest, it will serve to show the general range of working in which the gas and the turbine plant will respectively predominate. The assumptions upon which this comparison is based, are given in Table II, the costs are embodied in Fig. 4, and the relative saving in Table III.

At the price of coal prevailing in Richmond, the gas plant shows 13 per cent. gain over steam at full load, and 5 per cent. at half load. Owing to the handicap of higher fixed charges, the turbine plant naturally shows a lower power cost with low-priced coal; that is, where freight rates are low. But even a mine operator is not justified in charging himself for power fuel *less than the prevailing market price* (f.o.b. mines). For the high-grade fuels, the mine rates are about $1.25 for run-of-mine and $0.90 for slack and screenings. Hence, in reality, this gas power system influences an extensive field. It is evident from the diagram that a less efficient prime mover than the steam turbine would show a cost-line lying not only above but at a greater inclination than the turbine line, which would bring the point of equal cost between gas and steam to a still lower price of coal, and largely increase the saving. In Fig. 4 the crossing of the steam and gas lines indicates the starting point of gas power work—$1.25 coal for a fully loaded plant, and $1.90 at half-load. Or, considering the matter in another light, with steam coal at $2.70, we could afford to pay about $4 for gas coal for the same cost of power.

On the other hand, with light loads or fluctuating loads averaging but a fraction of the generating capacity, the gas plant is evidently at a disadvantage. And for this reason the turbine plant still finds exclusive application in all service subject to extreme overloads of variations. In fact, with the extension of a large electric power system, such as at the Richmond works, it is possible that a combined gas-engine-turbine plant may best meet load requirements with the highest resultant economy, the turbine unit carrying fluctuating peaks and the gas engines the uniform load, as suggested by Mr. H. G. Stott. At present, hot gas-engine jacket-water is utilized directly for boiler feed in an auxiliary air-compressing plant, although charged for in the cost table. This arrangement would, of course, be even more applicable to the combined plant, permitting most of the auxiliaries to be motor-driven without loss of heat for feed water.

## DISCUSSION ON "WORKING RESULTS FROM GAS-ELECTRIC POWER PLANT. REPORT OF 30-DAY TEST ON SERVICE PLANT, RICHMOND WORKS, AMERICAN LOCOMOTIVE COMPANY." ATLANTIC CITY, N. J., JULY 1, 1908

**J. P. Jackson:** I have found, as I presume all who have dealt with gas power-plants have found, that the first question to be determined is that of reliability. Is it possible to have a plant that will operate continuously with good service under all conditions, a plant that will not shut down on account of trouble of one kind or another, as gas plants have a habit of doing?

The first cost of gas plants has been referred to, and it is admittedly high. A steam plant can usually carry a heavy overload but it is difficult to equal such service with a gas plant unless the gas is exceedingly rich. If the gas is poor even less than rated load is sometimes obtained.

Flexibility and reliability of the auxiliaries are essential. Can a spark system be made reliable: a system that can be fixed, in case it gets out of order, without shutting down the whole unit? Probably, with proper duplication, that can be done. Compressed air is usually used to start gas engines. I think many gas plants have had trouble because the compressed air apparatus has not been independent, so that in case the air is lost in the tanks, they can be pumped full in a few minutes. Circulating pumps and coolers are needed, unless water is inexpensive. Such water is for cooling the engines and for use in the scrubbers and vaporizers. If a suction producer plant is under consideration, a blower is necessary to start the fire and also suitable arrangements must be made for cleaning fires, if it is desired to run twenty-four hours a day.

So far as I am able to observe, if a small gas plant is in good running order the labor is less expensive than in the case of steam plants, though in most cases, such plants being still in the experimental stage, there is apt to be extra expense which materially raises the labor account. I believe, however, that when we get the gas engine to the same point of perfection, the labor will probably be a less expensive item than in the case of the steam plant. In a plant with a large load-factor the fuel cost will be less than that in a steam plant of small unit or size. The saving in coal has to be offset against other items, however. The cost of water is important, inasmuch as a water cooler and condenser must be used.

Deterioration and repairs have been enormous items of expense, which can be eliminated to a large extent. There is no reason why a well-designed gas engine cannot maintain its brasses, instead of having them eaten out by sulphuric acid; why it cannot continue to run with about the same stability as a steam engine.

So far as making the gas goes, producers for gas purposes are undoubtedly less expensive to keep up, and they need less attention than steam boilers. They cost less originally. In gas plants there are needed gas testers that continuously record the character of the gas; these are as necessary as gauges in a steam plant to record the steam pressure. Suction gauges are scarcely sufficient.

I have spoken of troubles, because they have come forcibly to my notice. But I believe that so far as reliability of service goes, it should be possible to build a producer plant which will give just as reliable service as a steam plant, especially for small units in locations where the price of fuel is high. The annual cost, including depreciation on the higher first cost, labor, and fuel, and every other item of expense, should be in many cases less for the gas plant than for the steam plant.

**J. R. Bibbins:** The ability of a gas-power plant to carry overload is entirely a question for the designing engineer to decide. The maximum capacity of a gas engine is reached when the cylinder is full of mixture of maximum density; this is analogous to a steam engine taking full-stroke steam. At the present time engines of good construction are rated with a continuous overload capacity of from 10 to 15 per cent. In the plant at Richmond the engine has sustained a one-hour overload of over 30 per cent, or a three-hour overload of 19 per cent. These results were obtained with good gas, but conditions are not always so favorable, and conservative builders lower their ratings in order to cover contingencies entirely beyond their control. In fact, this particular engine has about 20 per cent excess capacity. A knowledge of future operating conditions would undoubtedly have enabled the designer of this plant to take advantage of this in electrical ratings.

The steam turbine, as built to-day in America, is exerting an embarrassing influence on the question of gas-power ratings, as American practice is extremely conservative. Compared with German practice, for example, it will be found that foreigners are much less conservative in overload ratings, as determined by temperature guarantees. If the same basis of rating existed for domestic machinery as for foreign generating machinery, even turbines, American practice in gas-engine ratings would not be so generally criticized, and the prime mover would not be called upon to compensate for deficiencies in plant equipment or operation. Standardization of gas-power practice is now being considered by the American Society of Mechanical Engineers. A committee was appointed last December, and within the next year it is probable that American practice will be well defined and placed upon a more logical basis than at present exists, where nearly every manufacturer has his own standards.

The principal object of the paper is to present some definite data on the operation of the modern plant, properly equipped and operated, data which clearly refutes the general charge of unreliability and costliness so often encountered. Such charges are usually based upon individual experience or general misinformation. There is nothing unusual about the Richmond installation—a standard type of gas engine—a simple form of bituminous producer with independent auxiliaries for tar removal. The plant is capable of continuous operation through the use of water-seals at the producers; the lubrication and cooling of the engine are automatic; the ignition system is in duplicate; and the governing fully as sensitive as in standard steam practice—2 to 2.5 per cent variation of mean speed. Although a direct-current installation in this instance, the regulation obtained from this type of engine is sufficient to permit alternating current parallel operation without the use of spring couplings.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 1, 1908.*

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# FROM STEAM TO ELECTRICITY ON A SINGLE TRACK ROAD

J. B. WHITEHEAD

As bearing on the general problem of conversion from steam to electricity for railroad operation, attention may be drawn to the probable influence of the methods followed and results obtained in equipping single-track roads. Of the total mileage in this country, about 60% is single track. The conditions obtaining on such roads are necessarily widely different from those on the large trunk-line sections which have been recently electrically equipped. While the several notable papers which have recently appeared on this and kindred subjects have taken quick advantage of the data available from the short periods of operation of several large installations, it cannot be said that the conditions in those cases are typical of more than a part of the entire problem.

Between the interurban road of comparatively light units and the large trunk-line installation with locomotive equipment, there is an intermediate class of steam road which, if equipped with electricity, should furnish excellent indication as to the results to be expected in the larger projects. These roads have usually single track and operate combined passenger and freight traffic over moderate distances. Unfortunately, the change in this type of road cannot often be made attractive on the ground of increased economy of operation; the transfer is usually accompanied by such an increase in fixed charges as to more than offset the economies possible under electrical operation. The road described in this paper is no exception in this respect, but, as is often the case, other considerations were deemed important enough to justify the change to electricity. The road has a long steam history which should permit excellent opportunities for comparison of results under steam and electricity. The considerations leading to the adoption of the 6600-volt, single-phase, alternating-current system are given at some length; opportunity is taken to review the authority for several engineering constants commonly accepted; and an estimate is made as to the probable effect of the change on the cost of operation.

*The road.* The Annapolis Short Line, a property of the Maryland Electric Railways Company, is a single-track, standard gauge steam road between Baltimore and Annapolis. Its length is 25.25 miles and in addition there is a branch 4 miles long extending south of Annapolis to Bay Ridge, a summer resort on Chesapeake Bay. The Baltimore terminal is Camden Station, the main terminal of the Baltimore & Ohio Railroad. At Annapolis the entrance is direct into the Short Line's own terminal, at which point are located its shops, roundhouse, car barns, etc. The maximum gradient is 1.5%, the longest stretch at this figure being 1.5 miles. There is one curve of 8°, one of 6°, several of 4° 30′, and many of easier figure. There are three bridges, one of them, over the Severn River being 3700 ft. long and two have draws. The rail is 80 lb.; the ballast gravel and cinder. The present normal service comprises seven trains per day, averaging three coaches each, in each direction. The approximate monthly car-mileage is 30,000. The fastest time is 45 minutes between terminals with 5 intermediate stops, a schedule speed of 33.7 miles per hour. There is one train per day of this class in each direction. The local running time is 1 hour with an average of 15 stops, a schedule speed of 25.25 miles per hour. There is one freight train each way daily and there are occasional large excursion loads.

Aside from the demands of a constant high-class patronage between the two cities, the conditions imposed by operation over more than a mile of the crowded B. & O. R.R. tracks and into its terminal, have resulted in excellent operating efficiency and schedule maintenance.

*Reasons for change to electricity.* The objects sought in changing to electrical operation were increased car-mileage, more frequent service, express service at least as fast, cleaner service, and the sentimental and indefinable attraction inherent in electrical operation. It is evident that the first three of these objects could be attained with much less initial expenditure by increasing the rolling stock, double tracking, installing block signals, etc. Difficulty might be met in the Baltimore terminal of the B. & O. R.R., where the number of train movements in and out attendant upon turning a locomotive and the time consumed, are already limiting factors. It would appear, however, that this difficulty also might be met by the use of double-end locomotives.

Elsewhere in this paper a comparison is made of operating expenses, maintenance, and interest charges for steam and electric operation of the present schedule. The comparison indicates that the operating and maintenance expenses alone would be about the same in the two cases; with interest charges included, however, the total of these items combined would be increased about 16% in changing from steam to electricity. While a part of this increase is due to the high price paid for power, it will be evident, notwithstanding, that the conditions are not such as to offer any prospect of increased economy of operation by electricity. Reasons are present, however, which in the eyes of the controlling interests are sufficiently cogent to more than overcome this objection, and to justify the abandonment of steam.

Owing to the fixed nature of the traffic to and from Annapolis, and to the fact that the local business is only 25% of the total, the direction in which increased business may be looked for is in the development of the region between the two cities. As the road runs for about 8 miles along the north side of Round Bay and Severn River, through high and attractive country, the prospect is unusually good and already attested by the rise in real estate values. It is believed that this development, slow in the past under steam, will be an early result of frequent electric service. Further, the aim is to develop excursion business to Bay Ridge to a degree not possible with steam. The superiority of electricity for this class of service is well known. Finally the Washington, Baltimore & Annapolis Railroad, to a certain extent a parallel line, and formerly a steam road, is also changing to electricity and is extending its tracks to city streets at each end. The distance from Annapolis to Baltimore by this route is about 15% greater than by the Short Line, and the latter has at present about 80% of the through business. The two roads are not competitive in local business, as they lie on opposite sides of the Severn River. The practical necessity for electrification on the part of the Short Line is evident. This, therefore, is one further instance in which the adoption of electricity is caused not by any prospect of better economy of operation, and not because it was more attractive in first cost than steam for increasing service. The reasons are found in special local conditions, and in the confidence that electric service will increase business to a degree not possible with steam.

*Power supply.* There are in Baltimore two 25-cycle, 13,200-volt, three-phase power plants. One, operating the street railways, has 35,000 kw. installed; the other supplies the larger part of the city's lighting and power and has 13,000 kw. installed. This latter plant is on the Annapolis Short Line about 1.5 miles from Baltimore. Each of these companies has an arrangement for receiving power from the Susquehanna development. Under these circumstances it was decided to purchase power. A contract, several features of which will be mentioned later, was entered into with the latter company whose plant lies on the line of the road.

*Type of car.* To meet the present daily passenger car mileage, single-car trains on one-half hour headway in the busier morning and afternoon hours, and on hourly headway at other times are proposed; through expresses and locals will alternate. A description of the car adopted is not necessary here, and may be had elsewhere. It may be stated, however, that it is of a type and design specially chosen to meet the demands of the required high-speed service. The center, intermediate and side sills are of steel. Wheels, trucks and couplers are according to M. C. B. standards. Train control is provided for both air brake and electric equipment. The car is of the Pullman type. The electric control is on one side of the vestibule and is enclosed at the rear end by a door, which when operating in the forward direction serves to seclude the motorman. The express car seats 62 passengers, is 55 ft. long, and the body alone weighs about 32,000 pounds. By multiple unit train control two-car trains on the above mentioned schedule will double the present car mileage. Moderate excursion loads may be handled with the equipment as installed. For possible concentrated loads steam will be relied on.

*Available systems.* In estimating the relative advantages of direct current and alternating current systems for the service, it was considered that the single-phase system is the only available alternating current system which has shown itself commercially successful in this country, and that the direct current system has no advantages so far as actual operating conditions are concerned. On the other hand the 1200-volt direct current system was not considered, since it does not offer a sufficient number of examples from which deductions as to operative success may be drawn. The choice of system was therefore based on a comparison of the available single-phase 25-cycle system and the 600-volt direct current system. This comparison was made from the standpoints of first cost and operating expenses; under the latter are included power consumption, station attendance and maintenance of equipment. As the physical differences in the two systems are not limited to the car and station equipments, but extend also to the distributing and return conductors, a somewhat detailed study of the effects in these two portions of both systems was made with special reference to the values of constants as given by several authorities. The constants for rail return and alternating current trolley drop vary rather widely in the literature of the subject. The following comparative figures are tnerefore not without interest. A note on the train resistance of single cars is also given.

## DISTRIBUTING CONDUCTORS

*Direct-current rail return.* Owing to indeterminate values of the resistance of the paths of currents actually passing to earth, and of increased conductivity due to rail joints, the results of tests on contacts between bonds and rails and the values of bond resistance do not lead to reliable results when applied to the calculation of the resistance of rail return. Data from existing tracks are available however and show a rather wide difference of opinion as to permissible resistance of joint. Parshall and Hobart in "Electric Railway Engineering" place the resistance of "well-bonded track" at 5% greater than calculated continuous rail. One well-known road of this country replaces a bond if it shows a resistance higher than that of 3 ft. of rail, *i.e.*, about 10% of continuous rail, and tests on its track show the bond resistance to vary between 24 inches and 14 inches, or in the neighborhood of 6% of rail. Another conspicuous road places the defective limit as high as 5 ft. or 15% of continuous rail, with rails bonded to full capacity. The Electric Railway Test Commission Reports show that for single track laid in cinders and bonded to 17% of its conductivity the measured resistance is about 36% greater than the value for continuous rail. In this case, however, the bond was outside the angle bar and 30 inches long. The measured value is less by 3% than the calculated sum of rail and bond, even with contact between rail and bond assumed as zero. This indicates leakage to earth and increased conductivity due to rail joints. To estimate the resistance of the same track with bonds 12 inches long, a calculation was made assuming the 30-inch bond as one branch of a divided circuit, the other branch being the joint plates and stray paths. The resistance of the stray path was thus determined. For this track, then, bonded to 17% of its capacity with bonds 12 inches long, the resistance would be that of continuous rail plus 11%. Bonded to 34% of equivalent copper and with bonds 12 inches long, the resistance would be that of continuous rail plus 6.6%.

In view of the above we may take as attainable values of track return with 12 inch bonds the resistance of continuous rail plus 15% when bonded to 17% of the equivalent copper; the resistance of continuous rail plus 10% when bonded to 34% of equivalent copper; and when bonded to full capacity and under best conditions of maintenance the value may be as low as that of continuous rail plus 5%.

*Alternating-current distributing conductors.* We may conveniently consider the effects in trolley and track at the same time. When carrying alternating current the rails are the seat of reactance as well as resistance. Numerous tests have been made for determining their values. These tests differ somewhat, as the phenomena depend largely on the current density and on the shape of section and material of the rail. Perhaps the most pretentious tests are those of the Electric Railway Test Commission at St. Louis. It is to be regretted that these tests were not made on a track which conformed more nearly to present standards and were not more carefully prepared for publication. The report on this portion of the work presents many inconsistences and omissions; and a 30-inch 2/0 bond can scarcely be said to be common in practice. There is, however, much of value in the published account of the tests.

The drop in a single track of 56-lb. rails, and with the trolley 18 ft. above the rails at 25 cycles and 200 amps. is given by the Railway Test Commission as 122 volts per mile, with a total power factor of .60. The total reactance volts are about 97.6, of which 38.6 are due to the rails and ground, (as shown in a separate test) leaving 59 reactance volts per mile due to the field between trolley and track. The current density of 200 amperes has been chosen here for comparison of values since it represents approximately the maximum alternating trolley current which will be reached on the road under investigation.

Parshall and Hobart in " Electric Railway Engineering " give the following figures on page 285.

At 25 cycles, 4/0 trolley, 20 ft. above track

Impedance volts per 100 ampere per mile, 80 lb. rails = 76.5
" " " " " " " 60 " " = 75.3

These figures are higher than those of the Railway Test Commission. This is largely due to the large value of the ratio of alternating current to direct current drop in the track, Parshall and Hobart giving 8.1 and the Test Commission Report giving 5.5 for the same weight of rail. The sections of rails, however, are different and the current density is not given by Parshall and Hobart although this ratio depends largely on current density. That these large values of this ratio do not have a greater effect on the impedance of trolley and track is due to the comparatively high ohmic resistance of the trolley. Thus in the calculation given hereafter for 80 lb. rails the total drop at 160 amperes per mile at 25 cycles is about 64 volts, the direct current drop in the trolley would be 33 volts, and in the track 3.2 volts, giving as the ratio of alternating current to direct current drop for trolley and track about 1.85. Parshall and Hobart's figures indicate the small influence of the difference in weight of rail on the total impedance, although the impedance of the rails alone increases markedly with the weight.

One of the manufacturing companies places the drop per 100 amperes per mile in 3/0 trolley and 80 lb. track at 62 volts, height of trolley not stated. This figure is practically the same as that given by the Railway Test Commission for very different weight of rail and type of bond.

The above figures are at considerable variance. This is probably due in some measure to the difference in conditions of the several tests on which the figures are based. It is possible that the conditions in practice as dependent on the proportion of trolley current returned by the rails, may vary with the locality to a degree sufficient to account for the differences in the values of the voltage drop in trolley and track. It may not be without interest therefore to investigate by calculation the values to be expected.

The inductive component of the voltage drop is due to the aerial reactance and the reactance in the rail itself. The watt component is due to the resistance of trolley and track and to iron losses in the rails. The calculation is simple if all the return current be assumed to be in the rails and the values for rail iron loss be taken from published tests. The reactive volts at 25 cycles per mile of line of two wires of radius $r$ and distance apart $d$, carrying current $i$ in amperes are given by the expression $0.101\, i \log \frac{d}{r}$. One half of this value is due to each wire. We may take this expression as a basis for calculating the aerial reactance electromotive forces. Owing to the wide difference in nature of the overhead and return conductors we may consider them independently both as regards energy and reactance electromotive forces.

The most common type of trolley suspension for roads of the class here discussed is the single catenary. It is necessary to consider the influence of the suspension cable. Within the limits of accuracy of this calculation it will be sufficient to consider this cable as parallel to and at its average distance from the trolley wire. Let $R_1$ be the resistance per mile of the suspension cable, $r_1$ its radius, $d_1$ its distance above the rails, and $i_1$ the current flowing in it. The same letters with subscript 2 refer to the trolley wire. If $i$ is the total overhead current, we have two equations for determining $i_1$ and $i_2$. We may conveniently use Steinmetz's symbolic method of notation

$$\underset{.}{i}_1 R_1 - j\,.05 \left(\underset{.}{i}_1 \log \frac{d_1}{r_1} + \underset{.}{i}_2 \log \frac{d_2}{r_2} - \underset{.}{i}_2 \log \frac{d_1 - d_2}{r_2}\right)$$

$$= \underset{.}{i}_2 R_2 - j\,.05 \left[\underset{.}{i}_2 \log \frac{d_2}{r_2} + \underset{.}{i}_1 \left(\log \frac{d_1}{r_1} - \log \frac{d_1 - d_2}{r_1}\right)\right] \qquad (1)$$

$$\underset{.}{i}_1 + \underset{.}{i}_2 = i \qquad (2)$$

The former equation expresses the equality in messenger cable and trolley of the total drop between station and car. Equation (2) expresses the total current as the vector sum of the currents in the two conductors. Solving we have:

$$\underset{.}{i}_2 = \frac{i\left(R_1 - j \log \frac{d_1 - d_2}{r_1}\right)}{(R_1 + R_2) - j\left(\frac{\log\,(d_1 - d_2)^2}{r_1\, r_2}\right)}$$

This expression does not contain either $d_1$ or $d_2$ explicitly, only the difference of these quantities appearing. Thus the division of current between trolley and messenger is independent of the height above the track. The effect of the field of the track current on this division is negligible for the values of $d_1$ and $d_2$ met in practice. For 3/0 trolley wire, and $\frac{7}{16}$ in. steel suspension cable we have $R_1 = 3.7$, $r_1 = 0.218$ in. $d_1 = 22.875$ ft., $R_2 = 0.326$, $r_2 = 0.205$ in., $d_2 = 22$ ft.
For $i = 100$ we have

$$\underset{\cdot}{i}_2 = 91.5 + j\,4.04;\ i_2 = 91.6$$

$$\underset{\cdot}{i}_1 = 8.5 - j\,4.04;\ i_1 = 9.4$$

Substituting these values in either side of equation (1) we find the drop per 100 amperes per mile in trolley and messenger cable is

$$\underset{\cdot}{E} = 30.58 - j\,32.76;\ E = 44.75.$$

This value will vary with the height of the trolley. The variation is small, however, if $d_2$ is above 20 ft, and formula (1) readily permits its calculation.

If the suspension cable is neglected as a conductor the value of the above drop is

$$\underset{\cdot}{E} = 32.6 - j\,36;\ E = 48.5$$

In considering the track return we face the uncertain distribution and value of its magnetic field, consequent aerial reactance, and the proportion of total current carried by the track. Assuming 100 amperes in each 80 lb. rail and assuming that the magnetic field outside the rail is the same as though all the current were concentrated at the center of the web, and applying the above expression for aerial reactance, we have as the reactance volts due to the field set up between track and trolley by the track current about 32 volts. This value takes due account of the mutual induction between the two track rails. The reactance volts within the two rails, as deduced from the results of the Railway Test Commission's tests on 80 lb. rails are 21. The total reactance volts in the track are thus 53, for trolley 22 ft. above track and total current 200 amperes. The ohmic drop in the rails and bonds is 6.45 volts; the component of rail drop due to iron loss is 22.4 volts (Cf. Report Rwy. Test. Comm.). The total watt component of drop at 200 amperes in the track is thus 28.85 volts. The electromotive force per mile per 100 amperes in the track is, therefore expressed by $E_t = 14.42 - j\ 26.5$. Adding this to the complex expression for the drop in the overhead conductors we have as the total drop $E_0 = 45 - j\ 59.26$, or $E_0 = 74.5$ volts per 100 amperes per mile. If all the current were carried by the trolley wire the value would be $E_0 = 47 - j\ 62.5$, or $E_0 = 78$. These figures also assume all of the return current to be in the track. This latter figure is remarkably close to that given by Parshall and Hobart, although the several components differ widely. Their value for the track is $7.7 - j\ 27$ and for the trolley $34 - j\ 37$. They have apparently not considered the secondary losses in the rails, nor the effect of suspension cable in reducing trolley reactance and resistance.

The numerous tables given by Parshall and Hobart showing the properties of rails and track as conductors for alternating current, indicate a very unfavorable comparison with the same properties when conductors of direct current. The basis of the tables is not definitely stated, however, and the values are not always in accord with published tests from other sources. To mention only one case, the drop per mile in 100 lb. rail carrying 100 amperes is given as 59 volts. The results of the Railway Test Commission give 41.5 volts for 80 lb. rail.

It is evident that in the particular case which we have considered the value arrived at is too high, for, as is well known, all of the return current does not flow in the rails. The results of an unpublished test of which the author has knowledge indicated the track current to be in places as low as 40% of that in the trolley, the average proportion being 50% or 60%. The conditions affecting this proportion vary so widely as to make it difficult to estimate the effect of this current dispersion on the reactance of the circuit. Let us assume, however, that $p$ is the fraction of the trolley current in the rails, and that the iron losses and reactance within the body of the rail vary directly as the current at the low densities here used. (Cf. Report Railway Test Commission). Then the only indeterminate quantities entering into the value of the total drop in trolley and track are the reactance volts due to the trolley current as affected by the position of the mean path of the stray current in earth, the reactance volts due to the track current, and those due to the stray current. If for the purpose of investigation we make the not too violent assumption that the earth current distributes itself so as to be of circular cross-section tangent to the surface at the track, the first of these quantities increases and the last decreases with increasing radius of the circular section. The values of increased trolley reactance may be readily calculated from the right hand side of formula (1) by adding to $d_1$ and $d_2$ the value of the radius, $R$, of the assumed circular section of the stray current. The reactance volts due to the stray current are given by the expression:

$$\frac{0.101\, i\, (1-p)}{2} \log \frac{(22+R)}{R}$$

in which $i$ is the total current and $p$ the proportion of $i$ carried by the rails. The other components of the total drop are either unchanged or directly proportional to $p$. The following table of values of total drop indicates how far the drop is affected by variations in the value of $R$ and $p$.

| | Values of *p*. | | | | |
|---|---|---|---|---|---|
| Values of *R* | 1 | 0.8 | 0.6 | 0.5 | 0.4 |
| 1 | 74.5 | 71.1 | 67.8 | 66. | 64.4 |
| 2 | 74.5 | 70.9 | 67. | 64.9 | 62.9 |
| 5 | 74.5 | 70.6 | 66.1 | 63.7 | 61.4 |
| 10 | 74.5 | 71. | 65.9 | 63.3 | 60.8 |
| 50 | 74.5 | 72.9 | 67.8 | 64.9 | 62.5 |
| 100 | 74.5 | 76. | 69.7 | 66.7 | 63.8 |

The effect of diminishing values of $p$, as was to be expected, is to decrease the total reactance. Increasing values of $R$ first decrease, then increase the reactance. The stray current, if concentrated in a small section, has a magnetic field of appreciable value; consequently when the radius of section is small, increasing the radius causes rapid decrease in the field. For large values of $R$, however, the increased distance between trolley and resultant center of return conductor causes an increase in the total flux more than sufficient to compensate the above decrease. For all the values of $p$ given the reactance volts are at a minimum in the neighborhood of $R = 10$. So far as the writer is aware there is no evidence as to the distribution of the stray earth currents. This distribution is in all probability never the same in any two cases. The amount of the stray current is obviously also a variable, not only with the particular case, but also with the proximity to feeding points. What is of interest, however, is that the reactance values vary very little within wide changes of both $R$ and $p$, as is evident from the above table. Assuming the stray current to have a section of any radius between 10 and 50 ft., and $p$ to be .5, the reactance volts per 100 amperes per mile are practically constant at 64 with a power factor .60. An increase from .5 to .8 as the proportion of trolley current in the rails changes this value scarcely 10%, while for smaller values of $R$ the change is still less. With the assumptions stated the voltage drop per 100 amperes per mile at 25 cycles in 3/0 catenary trolley 22 ft. above track of 80 lb. rails is between 65 and 70 volts.

## TRAIN RESISTANCE

There is wide diversity of statement and figures on the magnitude of train resistance. Two recent conspicuous comments on this subject also are found in the Report of the Railway Test Commission and in Parshall and Hobart's "Electric Railway Engineering". In the following table the figures of these authorities are compared with those of Blood as given before the American Society of Mechanical Engineers, June 1903, and those of Armstrong (Trans. A.I.E.E., June 1903). The values given are for single cars.

Train Resistance—Pounds per Ton.

| Speed miles per hour.... | 0 | 5 | 20 | 30 | 40 | 50 | 60 | Single cars |
|---|---|---|---|---|---|---|---|---|
| Elect. Rwy. Test Comm.. |  |  | 12 | 15 | 20 | 26.8 | 35 | 38-ton car |
| Berlin-Zossen.......... | 15 |  | 3.3 | 7.7 | 17 | 15.4 | 18.3 | 90-ton and 77-ton car |
| Aspinall.............. |  |  |  | 9.4 | 12.7 | 17 | 22 | 90-ton and 77-ton car |
| Blood................. | 5 |  | 9.7 | 13.5 | 18 | 21.9 | 29 | 38-ton car |
| Blood................. |  |  | 9 | 12.3 | 16.1 | 20.5 | 25.2 | 50-ton car |
| Armstrong............. | 4 | 4.5 | 7.8 | 11.5 | 17 | 23 | 29 | 45-ton car |

Parshall and Hobart conclude that Aspinall's formula gives reliable values for single car operation owing to their agreement with the results of the Berlin-Zossen tests. Aspinall's values for lighter cars do not change materially; for a 22-ton car at 50 miles per hour the figure is 16 lb. per ton. The figures are markedly less than those of the Railway Test. Commission. The heavy cars and excellent track conditions of the Berlin-

Zossen tests undoubtedly account for the low values, and values for lighter cars and average track may not be deduced from them.

The values given by the Railway Test Commission are distinctly higher than those in general favor, and should, therefore, receive attention. Without further corroboration, however, they must be accepted with some reserve owing to the variations in the figures in the several tests and to the unseasoned nature of the track.

It is evident that shortly after starting, the value of train resistance reaches a minimum somewhere about 5 lb. per ton. With 91.1 lb. per ton for a uniform frictionless rectilinear acceleration of one mile per hour per second, the necessary tractive effort after the actual moment of starting is about 96 lbs. per ton. The familiar and convenient figure of 100 lb. per ton thus allows about 4 lb. per ton for rotational acceleration, head wind and defective track conditions. It is evident also that during the acceleration period train resistance consumes only a small part of the total tractive effort and that errors in the values chosen assume no great importance for short runs. In this paper Blood's formula has been used for speeds of 20 miles per hour and upward and 100 lb. per ton has been assumed necessary for an acceleration of one mile per hour per second.

### THE SYSTEMS COMPARED

The basis upon which the choice of system was made has been already indicated. The proper capacity of available motor for the service was first determined for each type of equipment. To this end typical speed-time, current-time, and power-time curves for the average local run were plotted for 4-motor equipments with available motors of 75, 100 and 125 h.p. capacity as based on their one hour temperature ratings. The gearing in each case was made as low as consistent with the desired express schedule, since the conditions offered no special advantage in adpoting different gear ratios for express and local service. The methods of plotting these curves are familiar and require no comment for the direct current equipment. The treatment for the alternating current equipment during the period of acceleration is necessarily somewhat different and an outline of the method followed is given below. The typical curves for 100 h.p. alternating current and 90 h.p. direct current equipments were plotted, these motors showing themselves suitable on the basis of motor heating already mentioned. Speed-time, current-time, and power-time curves for each type of equipment were then plotted for every local run in each direction, due account being taken of curvature, grades, limited speed on bridges, etc. The results of this series of curves are given in the accompanying tables, together with their extension to the distributing system and power station. The value of this rather tedious process has been questioned. In the present case it not only afforded by comparison an indication as to the value of the typical curve for the purpose of computing an entire project, but it also enabled a run sheet to be constructed which developed passing points at rather different places than would have been indicated by the usual straight lines of schedule speed. The latter point is of particular value in a single track problem as determining which sidings should be equipped with trolley. After fixing the regular schedule sidings, a drop-back siding was provided in each case so as to prevent a loss of time being communicated to opposite traffic. This resulted in the fixing of eleven sidings, one of which is one mile long and another a half mile long, and there are three miles of double track at the Baltimore end. The total length of track thus becomes about 33 miles.

In the case of the alternating current equipment the construction of the speed-time and motor current-time curves is according to the usual methods, for the portion of the run after the period of uniform acceleration, *i.e.*, after the full voltage is on the motors. The initial portion of these and other derived curves does not, however, permit the simple determination possible with direct current equipments. As the literature of the subject presents little or no treatment at this point the following is offered as a simple method, which, from the data available, appears to approximate the actual conditions sufficiently closely for the purposes of calculation.

The motor current may be assumed as constant during the period of uniform acceleration at the value corresponding to the speed at which the acceleration begins to fall off. This conclusion is based on a study of the curves given by Bright (*Elect. Jour.* Vol. II, No. 11, p. 651, Nov. 1905) which, so far as the writer is aware, are the only curves taken from tests heretofore published. The motor current curves indicate a current rising slightly by steps during the period of constant acceleration to a maximum and beginning to decrease before the period of constant acceleration ends. An inspection of these curves shows that the average value of the motor current during constant acceleration is slightly less than the value corresponding to the termination of the initial straight portion of the speed-time curve. Thus, by area integration the average current per motor from start to stop in one of the runs measured by Bright is found to be 332.2 amperes. The value of this average, if the current during uniform acceleration is assumed constant at its value at the end of that period, is 335.6. The two corresponding values of the root mean square motor current from start to start are 412 and 416.

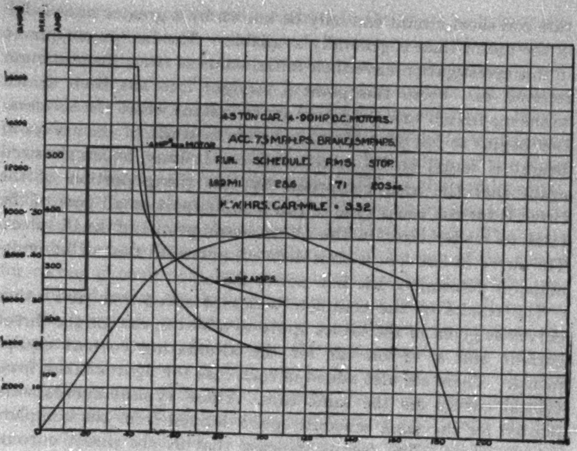
The initial portion of the line current curve will have a rising series of sharp changes corresponding to the voltage values of the several controller notches. The exact shape of this portion of the curve has no particular importance. The two aspects in which the line current must be considered are its maximum value as affecting line regulation, and the average value as determining the average apparent watts and the power factor. The maximum value is deduced from the maximum motor current and the ratio of line and auto-transformer voltages; it occurs then at the instant when full voltage is applied to the motors. The average value is found by the usual integration over its area, the average being taken for the period from start to cut-off. The shape of the initial portion should thus be considered in its effect on the area included by the whole curve. If, as already stated, the motor current is constant during this period, the starting value of the line current may be assumed as one-half its maximum value, since the motor voltage on the first notch is about one-half that on the last, a resistance automatically cut out limiting the first rush of current. The line current would then decrease slightly with increasing speed, increasing sharply at each controller notch. It may be safely assumed in calculation that a straight line between the above starting value and the maximum value gives the same area as the irregular curve just described. This suggestion is based on an inspection of the curves given by Bright and is sufficiently accurate, as the shape of this part of the curve affects the area only slightly in comparison with the remainder. The curve of motor kilovolt amperes is now determined. The line kw. at any instant is the sum of the useful mechanical output and the various losses. The mechanical output is the product of total tractive effort and speed, and when full voltage is on the motors is given directly by the motor curve of brake horse power with gears.

The losses to be considered are those in the gears and those due to copper and iron in motors, auto-transformer and car wiring. the losses in gears and motors are given by the curve of efficiency with gears. Those in the auto-transformer can only be determined from a knowledge of its characteristics. In the present case regulation and loss curves for the auto-transformer were furnished by the manufacturers. The values of the losses in the car wiring are here assumed as 1% of the total output. Following this method the portion of the curve for line kilowatts after full voltage is on the motors is readily plotted. The rising portion from the instant of starting, as in the case of the curves for motor current and line current, cannot be accurately predetermined owing to obvious indeterminate factors. Here, too, for the purposes of calculation it is sufficient to estimate its approximate form. Obviously the motor curve may not be used for the interval during which the motors are on the low voltage notches. The motor current, however, being approximately constant there, so is the net tractive effort, and the rise in speed being assumed to be uniform, the values of mechanical output are at once deduced and are seen to increase uniformly. At the instant of starting, the mechanical output is zero and the power drawn from the line is entirely dissipated in the transformer, wiring and motor. The voltage of the first transformer point is impressed on the circuit consisting of the starting resistance, the motor field and compensating winding and the stationary motor armature. The armature being stationary, there is a heavy loss in the short-circuit consisting of armature coil resistance leads and brush; this loss is of course greatest at standstill and decreases with increasing speed. The starting resistance also introduces a loss. In addition there are the normal copper losses in the remainder of the motor winding, the motor iron loss, and the losses of both types in the auto-transformer. The sum of these losses gives the initial value of the rising portion of the line power curve. It is manifestly impossible, and fortunately unnecessary, to determine this value accurately. We may note, however, that the value of the acceleration gives a value of the motor current, which as already stated, may with fair accuracy be taken as constant during this period. This current given, the motor and transformer curves give the normal losses when the motor is at speed, and thus a minimum value below which the initial line power cannot be. The increase due to starting resistance and armature coil short-circuit can only be known by a greater knowledge of the motor than is generally available. The line power curves in this investigation have their initial value as twice the minimum referred to. From this point a straight line has been drawn to the maximum value of power at the instant where the acceleration begins to fall off. Here, as before, a study of the curves of Bright is found to be corroborative. It may be emphasized again that the area comprised by this rising portion of the curve is for the usual type of run a sufficiently small part of the total to render error in the above assumptions of small effect. The curve of line kw. is thus derived, and with that of kilovolt-amperes determines the line power factor.

The results of the complete series of speed-time and other curves as given in the tables apply to a 37-ton car for the direct current and a 42-ton car for the alternating current equipments. There are also added in each case the figures taken from typical curves for the same cars. These typical curves were plotted for the same schedule speed derived from the complete set of curves. The results indicate that at the direct current car the average power consumption per car mile for the complete run is about 3.2% greater than shown in the typical curves. For the alternating current car the values of increase of complete run over typical run are 3.5% for kw-hr. per car mile. The typical run sheet therefore agrees very closely with the averages as deduced from the complete set. This is an interesting result, as the road is neither exceptionally straight nor level. The grades are generally up and down, and the two terminal cities are at virtually the same elevation. In the run which includes the Severn River bridge allowance was made for a reduction of speed to 10 miles per hour at the draw.

A continuous speed curve for the single-phase equipment was constructed for the express run between the terminals, with frequent coasts on grades, and a reduction of speed on the Severn bridge to 10 miles per hour. The average schedule speed was indicated as 42 miles per hour, the power consumption as 2.64 kw-hr. per car mile, and the average power-factor as 0.96.

In the case of neither of the cars above mentioned were the motors loaded to their continuous capacity. A later desire on the part of the management to increase the size of cars could, therefore, be met with the same motors, as is indicated by the figures in the tables for a 45-ton direct current car and a 50-ton


AMP
M.P.H.
45 TON CAR. 4-90 HP D.C. MOTORS.
ACC. 7.5 M.P.H.P.S. BRAKE 1.5 M.P.H.P.S.
RUN. SCHEDULE. RMS. STOP.
180 MI. 28.6 71 20 Sec.
K.W. HRS. CAR-MILE = 3.32
AMP² per MOTOR
LINE AMPS.
500
400
300
200
100
2000 10
20
40
60
80
100
120
140
160
180
200

FIG, 1

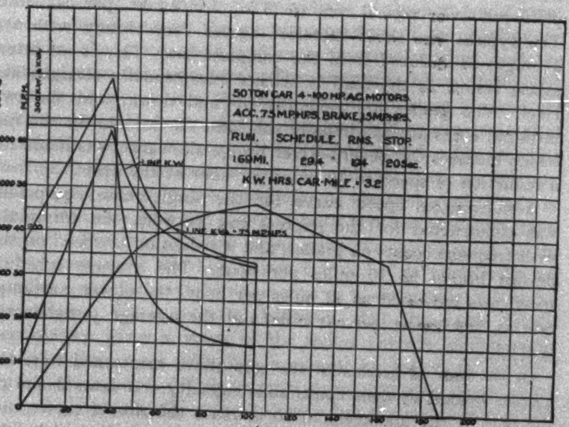

AMPS²
M.P.H.
30 K.W. & K.V.A.
50 TON CAR 4-100 HP. A.C. MOTORS.
ACC. 7.5 M.P.H.P.S. BRAKE 1.5 M.P.H.P.S.
RUN. SCHEDULE. RMS. STOP.
169 MI. 29.4 134 20 Sec.
K.W. HRS. CAR-MILE = 3.2
LINE K.W.
LINE K.V.A. - 7.5 M.P.H.P.S.
20
40
60
80
100
120
140
160
180
200

FIG. 2

## TABLE I.

37 Ton Car 4-90 h.p. direct current motors.

| Station | Distance | | Time sec. | r.m.s. motor cur. | Line cur. | | Line kw. | | Kw-hr. | | Watt-hr. ton-mile | Av. loss in line |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Feet | Miles | | | Start | Av. | Start | Av. | Run | Car-miles at motors | | |
| A | | | | | | | | | | | | |
| | 10,950 | 2.07 | 250 | 62.7 | 600 | 124 | 330 | 68.3 | 4.55 | 2.24 | 59 | 15.4 |
| B | | | | | | | | | | | | |
| | 7,950 | 1.5 | 213 | 93 | 772 | 243 | 425 | 140.5 | 7.55 | 5.08 | 137 | 8.55 |
| C | | | | | | | | | | | | |
| | 16,900 | 3.2 | 316 | 56.5 | 650 | 101 | 358 | 57.5 | 4.69 | 1.46 | 54.2 | 7.66 |
| D | | | | | | | | | | | | |
| | 3,800 | .72 | 121 | 87.8 | 710 | 186.6 | 390 | 102.7 | 2.88 | 4 | 108.2 | 20.1 |
| E | | | | | | | | | | | | |
| | 7,900 | 1.49 | 189 | 72.4 | 710 | 144.6 | 390 | 79.5 | 3.73 | 2.5 | 67.5 | 18.9 |
| F | | | | | | | | | | | | |
| | 12,400 | 2.35 | 274 | 72.3 | 710 | 165 | 390 | 91 | 6.42 | 2.73 | 73.8 | 11.9 |
| G | | | | | | | | | | | | |
| | 5,200 | .98 | 142 | 78.4 | 650 | 150 | 358 | 82.5 | 2.8 | 2.86 | 76.75 | 4.0 |
| H | | | | | | | | | | | | |
| | 14,800 | 2.8 | 303 | 64.2 | 710 | 143 | 390 | 78.7 | 6.2 | 2.22 | 60 | 11.9 |
| I | | | | | | | | | | | | |
| | 10,200 | 1.93 | 224 | 73 | 600 | 210 | 330 | 115.4 | 6.55 | 3.4 | 92 | 19.5 |
| J | | | | | | | | | | | | |
| | 7,200 | 1.36 | 172 | 75.3 | 650 | 181 | 358 | 99 | 4.17 | 3.07 | 82.6 | 14.5 |
| K | | | | | | | | | | | | |
| | 5,200 | .98 | 128 | 66.1 | 556 | 130 | 306 | 71.4 | 2.34 | 2.39 | 64.5 | 3.5 |
| L | | | | | | | | | | | | |
| | 9,110 | 1.72 | 241 | 54.2 | 512 | 75 | 282 | 41.2 | 2.54 | 1.47 | 37.6 | 2.96 |
| M | | | | | | | | | | | | |
| | 3,960 | .75 | 112 | 81 | 600 | 162 | 330 | 89 | 2.52 | 3.36 | 90.9 | 16.4 |
| N | | | | | | | | | | | | |
| Average | Sched. speed 29.6 m.p.h. | | | 72 | | | | 85.9 | 4.38 | 2.82 | 77.23 | |
| N | | | | | | | | | | | | |
| | 3,960 | .75 | 110 | 87 | 604 | 218 | 332 | 126.5 | 3.34 | 4.45 | 120 | 31.1 |
| M | | | | | | | | | | | | |
| | 9,110 | 1.72 | 257 | 81.7 | 604 | 194 | 332 | 111.5 | 7.33 | 4.26 | 115 | 17.9 |
| L | | | | | | | | | | | | |
| | 5,200 | .98 | 142 | 79.6 | 660 | 192 | 363 | 105.5 | 3.55 | 3.61 | 97.7 | 2.09 |
| K | | | | | | | | | | | | |
| | 7,200 | 1.36 | 172 | 67 | 604 | 141 | 332 | 87.5 | 3.69 | 2.7 | 73 | 7.9 |
| J | | | | | | | | | | | | |
| | 10,200 | 1.93 | 212 | 54 | 556 | 88 | 306 | 48.25 | 2.58 | 1.34 | 36.2 | 9.48 |
| I | | | | | | | | | | | | |
| | 14,800 | 2.8 | 270 | 68.6 | 604 | 206 | 332 | 113 | 7.81 | 2.69 | 72.8 | 16.9 |
| H | | | | | | | | | | | | |
| | 5,200 | .98 | 142 | 75.3 | 604 | 173 | 332 | 95 | 3.19 | 3.24 | 87.5 | 9.1 |
| G | | | | | | | | | | | | |
| | 12,400 | 2.35 | 240 | 66 | 604 | 163 | 332 | 89.5 | 5.48 | 2.33 | 63.2 | 3.12 |
| F | | | | | | | | | | | | |
| | 7,900 | 1.49 | 172 | 72.6 | 604 | 180 | 332 | 99 | 4.18 | 2.78 | 75.5 | 16.7 |
| E | | | | | | | | | | | | |
| | 3,800 | .72 | 119 | 73.6 | 652 | 149 | 359 | 82 | 2.25 | 3.13 | 84.9 | 20.3 |
| D | | | | | | | | | | | | |
| | 16,900 | 3.2 | 319 | 71.6 | 604 | 233 | 332 | 128 | 10.55 | 3.28 | 88.7 | 18 |
| C | | | | | | | | | | | | |
| | 7,950 | 1.5 | 183 | 66.6 | 712 | 101 | 392 | 55.5 | 2.46 | 1.63 | 44.2 | 1.77 |
| B | | | | | | | | | | | | |
| | 10,950 | 2.07 | 225 | 57.6 | 512 | 138 | 282 | 75.8 | 4.32 | 2.09 | 56.6 | 7.06 |
| A | | | | | | | | | | | | |
| Average | Sched. speed 30.3 m.p.h. | | | 70.7 | | | | 93.6 | 4.67 | 2.88 | 78.1 | |

## TABLE II.

42-ton car 100 h.p. alternating current motors.

| Car-miles | Watt-hr. ton-mile | Time sec. | Motor start | Current root mean square | Line cur. | | Line kilovolt-amperes start | Kilowatt-hours | | Line loss run | Kilowatt-hours |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Start | Av. | | Run | Car-mile | | At Transf. |
| 2.955 | 79.9 | 250 | 760 | 169 | 53.4 | 13.7 | 352 | 5.3 | 2.56 | 0.0556 | 5.36 |
| 5.77 | 156. | 213 | 950 | 236 | 65.6 | 24.2 | 434 | 7.8 | 5.2 | 0.0528 | 7.86 |
| 1.67 | 45.2 | 316 | 840 | 150 | 59. | 9.9 | 389 | 4.8 | 1.5 | 0.0085 | 4.81 |
| 5.64 | 152.6 | 121 | 920 | 208 | 70. | 17.1 | 426 | 3. | 4.16 | 0.0155 | 3.02 |
| 3.37 | 91.2 | 189 | 840 | 187 | 59. | 13.2 | 389 | 3.78 | 2.54 | 0.0297 | 3.81 |
| 3.34 | 90.3 | 274 | 880 | 189 | 62. | 15.9 | 408 | 6.8 | 2.9 | 0.0747 | 6.88 |
| 3.28 | 88.75 | 142 | 840 | 194 | 59. | 13.8 | 389 | 3.06 | 3.12 | 0.0505 | 3.11 |
| 2.73 | 73.8 | 303 | 840 | 168 | 59. | 15.1 | 389 | 6.42 | 2.29 | 0.0556 | 6.48 |
| 4.33 | 117.5 | 224 | 880 | 214 | 62. | 21.8 | 408 | 7.5 | 3.88 | 0.0248 | 7.53 |
| 3.81 | 106. | 172 | 880 | 221 | 62. | 21.1 | 408 | 5.25 | 3.84 | 0.0042 | 5.26 |
| 2.7 | 73. | 128 | 794 | 180 | 55.8 | 14.3 | 368 | 2.88 | 2.94 | 0.010 | 2.89 |
| 1.715 | 46.4 | 241 | 760 | 161 | 53.4 | 8.2 | 353 | 3.07 | 1.78 | 0.0287 | 3.1 |
| 4.28 | 115.9 | 112 | 880 | 225 | 62. | 17.9 | 408 | 3. | 4. | 0.0417 | 3.05 |
| 3.51 | 92.1 | 29.6 m.p.h. | | 195 | | | | 4.82 | 3.13 | | |
| 6.04 | 167 | 110 | 830 | 212 | 58.4 | 24.6 | 385 | 3.99 | 5.32 | 0.0372 | 4.03 |
| 5.37 | 145.1 | 257 | 880 | 219 | 62. | 19.3 | 408 | 8.2 | 4.76 | 0.0766 | 8.28 |
| 4.73 | 127.9 | 142 | 880 | 231 | 62. | 21.8 | 408 | 4.45 | 4.54 | 0.0356 | 4.48 |
| 3.2 | 86.5 | 172 | 840 | 197 | 59. | 15.5 | 390 | 3.94 | 2.9 | 0.0107 | 3.95 |
| 1.75 | 47.3 | 212 | 794 | 155 | 55.8 | 9.4 | 368 | 2.98 | 1.54 | 0.0436 | 3.03 |
| 3.47 | 93.8 | 270 | 840 | 205 | 59. | 22.6 | 390 | 9.55 | 3.41 | 0.0513 | 9.61 |
| 3.89 | 105.3 | 142 | 880 | 220 | 62. | 19.4 | 408 | 3.91 | 4. | 0.0573 | 3.97 |
| 2.605 | 70.5 | 240 | 840 | 197 | 59. | 18.3 | 390 | 6.7 | 2.85 | 0.0896 | 6.8 |
| 3.56 | 96.3 | 172 | 880 | 212 | 62. | 20.0 | 408 | 5.01 | 3.36 | 0.0461 | 5.06 |
| 4.28 | 116 | 119 | 840 | 195 | 59. | 13.2 | 390 | 2.22 | 3.08 | 0.0181 | 2.24 |
| 4.07 | 110 | 310 | 880 | 224 | 62. | 25.8 | 408 | 12.75 | 3.9 | 0.0257 | 12.78 |
| 1.826 | 49.4 | 183 | 920 | 187 | 70. | 11.4 | 427 | 3.06 | 2.04 | 0.0196 | 3.08 |
| 2.54 | 68.7 | 225 | 760 | 183 | 53.4 | 15.8 | 353 | 5.51 | 2.66 | 0.045 | 5.56 |
| 3.64 | 98.5 | 31 m.p.h. | | 204 | | | | 5.56 | 3.41 | | |

alternating current car. These figures are taken from the typical curves shown in Figs. 1 and 2. In view of the reliability of the typical curve as above indicated, the comparison of the two systems is based on these curves, due regard being had to the small percentage increases already mentioned. The comparative figures are given in the following table.

| Type of car | Schedule speed | Kilowatt-hours car-mile at car | Kilowatt-hours car-mile at sub-station |
|---|---|---|---|
| 37-ton direct current from complete runs | 30.3 | 2.85 | 3.58 |
| 37-ton direct current from typical curves | 30.3 | 2.76 | |
| 42-ton alternating current from complete runs | 30.3 | 3.27 | 3.31 |
| 42-ton alternating current from typical curves | 30.3 | 3.16 | |
| 45-ton direct current from typical curves | 28.6 | 3.32 | |
| 50-ton alternating current from typical curves | 29.4 | 3.2 | |

A further fact to be noted from a comparison of the two typical curves is that the alternating current car requires less power consumption for the run in spite of its greater weight. The two values of kw-hr. per car-mile are 3.2 and 3.32. This is due to the series resistance losses in the direct current car; owing to the short length of the run the motors are on resistance more than one-third the time during which power is applied. The maximum power reached for the single-phase car is greater, and so also is the power throughout the period when the motors are on full voltage. The former is, however, applied for a comparatively short time, and the direct current power is applied longer owing to the lesser value of maximum attainable speed. This difference does not obtain in the runs for the lighter cars. The direct current equipment on a 37-ton car accelerates with less demand and cuts off earlier than the alternating current equipment on the 42-ton car. Increasing the sizes of car to 45 tons and 50 tons imposes less additional demand on the single-phase motor than on the direct current motor of lower rating. The latter motor on the 45-ton car is worked well up to its figure for continuous rating, and it is questionable whether or not it is sufficient for the service. If the conclusions of the investigation pointed less strongly to the single-phase system, it would be necessary to consider a larger direct current motor before reaching a conclusion.

Increasing the figures for power by the percentages given above we have for values of kilowatt-hour per car-mile at the car, for the 45-ton direct current car 3.43 and for the 50-ton alternating current car 3.32.

The weights of the two cars are distributed as follows:

| | Alternating current. | Direct current |
|---|---|---|
| Car body | 32,000 lb | 32,000 lb. |
| Trucks | 21,000 | 21,000 |
| Motors and control | 32,000 | 22,500 |
| Air brakes | 3,000 | 3,000 |
| Live load | 9,000 | 9,000 |
| | 97,000 | 87,500 |

## STATION EQUIPMENT AND POWER CONSUMPTION

*Single-phase system.* In the alternating current system the starting current per car, assuming that the rate of acceleration is constant, varies with the track conditions. On level track the line current per car at 6600 volts is 57 amperes at 0.75 miles per hr. per sec. and 70 amperes at 1 mile per hr. per sec. at a power factor of 0.80 or better. Assuming the use of the available 3/0 catenary construction, and the voltage drop per 100 amperes per mile as 70 with a power factor 0.60 and a maximum permissible drop of 10%, it is evident that a two-car train may accelerate at 1 mile per hr. per sec. when fed by a single trolley at a distance of about 6.75 miles. The schedule is based on an acceleration of 0.75 miles per hr. per sec. and the equipments chosen will operate satisfactorily at considerably greater values of drop. The bunching of cars in such a section should therefore offer no difficulty on this score. A substation was located at a convenient station 6.25 miles from Annapolis and 17.4 miles from Westport. Using the figures already given, two cars starting at Annapolis at 0.75 miles per hr. per sec. will cause a maximum drop of 7.6% when fed from this substation. The line impedance at power factor 0.60 increases the reactive component of the car demand but slightly. If the car power factor be taken as low as 0.80, the load at the substation has a power factor 0.78.

Considering the resort Bay Ridge, 4 miles from Annapolis, the substation might with better advantage be located nearer Annapolis. This would, however, increase the starting drop in the region between power house and substation. As single cars may be readily started at Bay Ridge when fed over the above distance, and as the equipment of this branch is as yet undetermined, this question is of little importance. Future extension to Bay Ridge may be accomplished by an extension of the transmission line and the installation of a temporary or portable transformer substation. The above location of the substation as one trolley feeding point and the powerhouse as another meets the requirements of regulation satisfactorily.

The power house at Westport, 1.6 miles from Baltimore, as the feeding point for the north half of the line, although not located to the best advantage from the standpoint of symmetrical feeding, saves the building of a second substation. An effort was made with the power company to permit the load to go directly on the station bus through two-phase three-phase transformer connection. This would result in an average uniform distribution of load on the three-phases, but also in possible short applications of large fractions of the total load on one phase. The form of contract permits this, but the power company's distaste for unbalancing is shown by a further stipulation that the maximum demand shall be reckoned as three times that on the most heavily loaded phase. As the total installed capacity in the powerhouse is 13,000 kw. and as the maximum starting demand of the normal daily schedule may reach 1800 kilovolt-amperes, this attitude is not to be wondered at. It is increasingly evident that there are few cases where a single-phase railway, with the usual erratic combinations of starting peaks, may be supplied from a system furnishing at the same time light and power for other purposes. None of the polyphase-single-phase transformations recently reviewed by Armstrong (PROC. A.I.E.E.) will prevent occasional excess demands on one phase. Also some of these methods have the additional disadvantage of largely increased reactance drops with unbalanced loads. The problem narrows down to isolated generators for the railway load, or motor-generators for distributing the load uniformly, whatever its value. The former alternative was out of the question in the present instance, the units in the powerhouse being 2000 kw. each. It is, therefore, evident that the adoption of the single-phase system for this road meant the building of its own power plant or the installation of motor generators.

Aside from the question of efficiency, the motor generator is not attractive when power is purchased, since power contracts always have their limit of life. In Baltimore, however, as already mentioned, there are two large plants of similar voltage and frequency characteristics, and the Susquehanna development will also deliver power there in the same form in the near future. The likelihood of having the motor-generators left without a proper source of power is therefore remote.

The power and distributing system for single-phase equipment then resolves itself as follows: synchronous 13,000-volt 25-cycle 3-phase motors direct-coupled to 6600-volt 25-cycle single-phase generators. The trolley is fed directly from the generators, as are also step-up transformers for the 17.5 mile transmission to the substation.

The starting demand of a car varies between 375 and 475 kilovolt-amperes depending on the grade. Normal half hourly traffic requires four cars on the line at one time, with the possible bunching of three cars on one substation, or about 100% overload for two 300 kw. transformers. Three such units in the substation, and space and wiring for a fourth, will provide reserve capacity and provision for future expansion. The same transformer capacity is installed at the powerhouse. Excursion traffic should be handled by two car trains at lessened headway. Such trains would accelerate at a low rate. The running of nine trains on a 15-minute headway means a minimum of six on the line at once to preserve opposite traffic. The sustained demand if these trains are single cars will not exceed 1600 kilovolt-amperes. Two two-car trains and a single car starting at the same instant would impose 150% overload on three 300 kw. transformers. The motor generators obviously take the whole load. The sustained excursion demand above mentioned would be about 25% overload for 1200 kw. in motor generators. Three 600 kw. units will provide ample reserve and provision for considerable future growth.

For the comparatively short transmission distance there is no decided advantage in increasing the voltage above 22,000. If 33,000 volts is chosen, the size of wire is reduced to a point inadvisable from considerations of tensile strength and the difficulties and cost of insulation are also increased. Two transmission lines each of two No. 2 B. & S. wires 30 in. apart, and both lines carried on the same cross-arm, provide interchangeability and reserve capacity. With a load of 800 kilovolt-amperes at power factor 0.85 on two substation transformers, the drop between the power house 6600-volt bus and the substation trolley connection will be about 15%; the power factor at the station will be about 0.82. From the tabulated results of the complete local runs, the average efficiency of trolley and track is better than 98%, as shown by the values of kw-hr. per car mile at the car and at the substation. The loss was calculated by assuming that the average line current during the period while power is applied, is fed to a point one-third through the particular run in question. If the value of root mean square line current for the typical run is assumed to be delivered at the average distance of a car from a substation, the trolley and track loss is somewhat over 1.5%. In calculating these losses the energy component of track and trolley impedance as already given has been used. Assuming the average efficiency of the transformers at 96.5% and calculating that of the transmission line at 98%, we have half the total power supplied through the substation at about 89% and the other half fed directly to the trolley from the generator bus-bar at 98%. For the normal schedule already described the daily power consumption would be as follows:

| | |
|---|---|
| 22 locals at 3.32 kw. hr. per car mi. | 1840 kw-hr. |
| 20 expresses at 2.85 " " " " | 1401 " " |
| | 3240 |

One half of this at 98% and one half of 89% gives 3475 kw. hr. at the generator bus-bar. At an average motor generator efficiency of 80% we have 4350 kw-hr. daily consumption for the proposed normal schedule under the single-phase system.

*Direct-current system.* The normal starting current of the car described above for the direct current system at an acceleration 0.75 miles per hr. per sec. is 516 amperes; for a two-car train approximately 1000 amperes will be taken at starting. With two cars starting and one running the demand may easily go to 1200 amperes. Assuming a maximum permissible drop of 25% and 600 volts at converters and supposing that the single 80 lb. track is bonded to full capacity (0.028 ohms per mile), something more than 2,000,000 cm. of copper would be necessary to supply 1000 amperes to a two-car train starting from Annapolis from a substation 3 miles away. Aside from the consideration of the cost of copper, however, the question of collecting the large current values, and the high speed to be reached, points at once to the third rail as the proper method of feeding. Assuming 80 lb. third rail bonded to 10% of equivalent copper as having a resistance of 0.044 ohms per mile, we have as the resistance of the third rail and single track 0.076 ohms per mile. With 600 volts on the third rail and a 30% drop, this will permit a distance of somewhere between two and three miles as the length of the end of the feeding system beyond the last substation. Assuming that two cars in starting take 1000 amperes, and that they will make the only demand on the end beyond the substation, it would be possible in the present instance to locate a substation at a convenient passing point, indicated by the proposed schedule, 2.8 miles from Annapolis. The northernmost feeding point would naturally be the Westport power house. The distance between these two stations would thus be 20.85 miles. Considering the possibility of operating with only one intermediate substation, it is to be noted that the distance between substations would then be approximately 10.5 miles. With three cars starting midway between two substations, which would be a common occurrence, the drop would be approximately 300 volts. This figure assumes also very low values for track resistance. On the above basis it is therefore inadvisable to attempt to operate with less than four substations. These would be located as follows: one at Westport, one at Winchester (2.8 miles from Annapolis) and two others between these. The greatest distance between substations would thus be 7 miles. With three cars starting midway between two substations the drop would be about 200 volts. It is worth noting that if the road were double tracked it would be possible to obtain satisfactory regulation with two substations.

In the matter of substation capacity, when the demand on one substation is that of two cars starting and one running, the demand is in the neighborhood of 760 kw. With three starting on one substation, the demand is 920 kw. At 100% overload the latter figure would necessitate 460 kw. capacity. Thus one 300-kw. converter would take care of the normal single car schedule, and two 300-kw. units in a substation would handle a schedule involving two-car trains in one direction, and would, therefore, constitute a certain spare capacity when considered from the standpoint of the normal single-car schedule. This reserve is, however, not so great as that allowed for the single-phase system. For the transmission line, if a resistance drop of 5% be allowed, the average normal load can be handled by a 22,000-volt, three-phase line of three No. 3 B. & S. wires.

From an inspection of the results of the complete set of run sheets it will be noticed that the efficiency of trolley and track has an average value of about 80%. This was, however, based on three substations and a smaller value of conductivity in the distributing system, thus obtaining less first cost at the expense of regulation. Taking the mean distance of a car from a substation as one quarter the distance between substations, and assuming the resistance of third rail and track as 0.086 ohms per mile, the car will be fed over a resistance of 0.114 ohms. The R M S line current for the typical run is 351 amperes. Using these figures the efficiency of trolley and track is in the neighborhood of 92%. The single ends beyond the extreme substations are not included in this value which may be considered high. Taking the efficiency of converters and transformers at 90%, of the transmission line at 95%, and the average efficiency of powerhouse transformers at 96.5%, we would have a resultant efficiency somewhat less than 76%. About three quarters of the total load would be supplied at this figure—one quarter would be supplied directly from the powerhouse at 82.8%.

On the above basis the average daily consumption of power for the normal schedule would be as follows:

22 locals, or 555.5 car miles, at 3.43 kw-hr. = 1900 kw-hr.
20 expresses, or 505 car miles, at 2.7 kw-hr. = 1363 kw-hr.

Of this total of 3263 kw. hrs., figuring three quarters at 76% and one quarter at 83%, we would have about 4200 kw. hr. as the average daily consumption under the direct current system.

### CHOICE OF SYSTEM

For the purpose of making a choice of system it is only necessary to consider those particulars in which the two systems differ. The most important of these are first cost and operating expenses, the latter including power consumption, station attendance and maintenance of equipment. Following is a comparison of the cost of the essential parts of the two systems, as outlined above, and for the most part based on prices asked from manufacturers to cover the specific cases. The copper was bought during the high market of 1907. This fact has no particular weight in throwing the advantage to either system, if the direct current system includes the third rail as conductor. The cost of the third rail is based on a comparison of the several estimates compiled by Gottshall in "Electric Railway Economics". The length of track, trolley and third rail is taken as 33 miles to include the double tracks at the north end and middle of the line and the sidings. The transmission line is about 3.4 miles longer for the direct current than for the single-phase system, and the figures for this item include poles. Converters with transformers are valued at $17.50 per kilowatt.

| | Direct current | Alternating current |
|---|---|---|
| 9 cars completely equipped | $107,300 | $149,300 |
| Catenary trolley, poles, wire and guys | | 75,000 |
| Third rail | 132,000 | |
| Transmission line | 65,000 | 36,000 |
| Powerhouse apparatus | 21,000 | 62,000 |
| Substation " | 39,000 | 8,000 |
| Substation buildings | 15,000 | 3,000 |
| Bonding | 18,000 | 11, 00 |
| | $397,300 | $344,300 |

In power consumption the two systems appear to be on an equal footing. This is rather surprising since the motor generators reduce the efficiency of the single-phase system very markedly. In this case this reduction is offset by the losses in rotaries, the excess loss in distributing system, and the increased power consumption at the car, due to the smaller motors and short runs. For longer local runs the single-phase power would go to higher values than that for the direct current system. The price of power is based on the maximum demand and the total consumption, and for the normal schedule would average about 2.3 c per kw-hr. The monthly excess of single-phase power would thus be about $100.

In the matter of station attendance the direct current system would require that of three substations, which have no counterpart in the single-phase system. Two men per station at $75 per month each would make this item $5400 per year.

The cost of maintenance and repairs of car equipments would be less in the direct current system. Recent figures indicate that 0.5 cent for direct current and 0.75 cent per car-mile for alternating current is a fair basis for comparison. At 30,000 car miles per month the excess of this item for alternating current operation would be $900 per year. These items represent the principal particulars in which the two systems would differ. Other less conspicuous differences may be embraced for the purposes of this comparison in a figure of 10.5% for fixed charges on the initial cost. This item presents then an advantage on the part of the alternating current system of $5565 per year.

Summarizing the above items, we find a total of $8,865 per year in favor of the alternating current system. The figures for cost of the alternating current equipment have been taken for the most part from prices actually paid for construction and apparatus, while those for the direct current system are estimated. The result is that there are several advantages possessed by the alternating equipment as installed which would represent a considerable increase in the figures for first cost and operating cost, if obtained under the direct current system. The equipment as installed provides considerably more substation and power station reserve capacity than was estimated for the direct current system. It provides for the possibility of feeding moderate loads at Bay Ridge, and increased feeding capacity to that point at moderate cost. To accomplish this with the direct current system would mean a considerable addition to the equipment as outlined. The regulation of the system as installed is better than that available with direct current. The schedule speed is somewhat better, or to express it differently, the initial cost of the direct current equipment should be increased by an amount necessary to cover a motor of capacity equal to the alternating current motor. No attempt has been made to evaluate the cost to the alternating current system of these several advantages.

## COMPARATIVE COSTS OF STEAM AND ELECTRICAL OPERATION

The company's statements of operating expense under steam were available for a period of several years. They are sufficiently detailed to invite an attempt at a comparative estimate of the cost of electrical and steam operation. The difficulties in the way of such an estimate are well known. In the present case the nature of the service is to be changed both in frequency and the size of units. The extent of these changes cannot be predetermined. The exact proportion of old rolling stock necessary to maintain the present schedule, and the proportion of new equipment, both in rolling stock and station apparatus, necessary to operate on an equivalent new schedule can only be roughly estimated.

In the following comparison the present normal steam schedule is assumed to require four locomotives and fifteen coaches. Under this schedule the maximum number of trains on the line at one time is two and a train averages three coaches; there are, however, occasional special trains. Under electricity the proposed maximum number of cars on the line at once for equivalent normal schedule is four, and the necessary charges are based on these assumptions. The operating expenses for a typical nine months of steam operation are given below; the only items discussed are those peculiar to steam operation.

| | |
|---|---|
| Conducting transportation | $43,366.49 |
| Maintenance of way | 22,129.46 |
| Maintenance of equipment | 12,159.08 |
| General expenses | 12,196.91 |
| | 89,851.94 |

The car-mileage during this period was 277,754 or 30,861 car-miles per month. The cost per car mile is thus 32.36 cents. The proportions of the above figures peculiar to steam operation are indicated as follows:

| | | |
|---|---|---|
| *Conducting transportation.* | | |
| Fuel | $13,692 | |
| Waste, water, and oil | 1,114 | |
| Trainmen | 11,776 | |
| Roundhouse men | 354 | |
| | $26,993, or | 9.71 cent per car-mile |
| *Maintenance of Equipment.* | | |
| Repairs to locomotives | | 2.13 cent per car-mile |
| " " coaches | | 1.76 " " " " |
| *Maintenance of way* | | 7.97 " " " |
| *Interest on equipment* peculiar to steam operation, including locomotives, coaches, 2 water plants turn-table, coal plant, etc | | 1.52 " " " " |
| The total of these items is | | 23.1 " " " " |

Each of the above items will be modified under electrical operation approximately as follows, the same car mileage being assumed:

| | |
|---|---|
| *Conducting Transportation.* | |
| Power, 1060 car miles per day | 7.86 cent per car-mile |
| Trainmen, 7 crews of 2 men | 3.90 " " " " |
| Signalmen and dispatchers | .5 " " " " |

| | |
|---|---|
| *Maintenance of Equipment.* | |
| Repairs to cars and equipments | 2.76 cent per car-mile |
| Transmission line, 3% of cost | .3 " " " " |
| Trolley 5% of cost | 1.02 " " " |
| Station equipment 3% of cost | .4 " " " " |
| *Maintenance of way* | 7.25 " " " " |
| The proportionate change in this item is based on the figures given by Stillwell and Putnam; as given here, bonds are included but not overhead construction. | |
| *Interest on Equipment* | |
| Eight cars, power apparatus, trolley and transmission line and bonding | 4.48 cent per car-mile |

The total of these items is 28.47 cent per car-mile, or an increase of 5.37 per car mile over the present figure for steam operation. This increase therefore represents an increased total operating cost of electricity over steam of about 16.6%.

Considering the possibility of compensating for the above increase in operating cost, it may be noted that during the last ten years the passenger traffic of the road has shown a consistent increase, amounting on the average to about 5.5% for the past year. There was therefore a large rate of increase in the earlier years of this period. Much of this increase must be attributed to the legitimate results of the facility of travel afforded by the increasing efficiency of the steam road. In spite of the persistence of the increased receipts from year to year a discussion with the management reveals a decided idea that the through traffic is about fixed in value. Notwithstanding an increase due to improved service the reduction in rates consequent upon competition is regarded as an offset such as to maintain the through traffic at a constant value.

As suggested before in this paper, it is to the local traffic that an increase of earnings is looked for. At present the earnings from local traffic represent about 25%. The ratio of operating expense to earnings is about 65%. With the above increase of operating expense and assuming no increase of traffic, the ratio of operating expense to earnings is increased to about 76%. It is only necessary, however, to assume that the local traffic will double, to reduce the ratio of operating expense to earnings to less than its present value. As there is practically no competition in local traffic, the results of frequent electric service in other localities indicate that such an increase in local traffic in this instance is not improbable.

It would seem, therefore, that considering passenger traffic alone, notwithstanding the fixed charges on the investment, on a road with traffic of the nature indicated in this case, the substitution of electricity for steam is well worth considering.

## CONCLUSION

Outlining briefly the results of the discussion in this paper, there may be mentioned besides the general description of the road and the considerations leading to the adoption of electricity the following:

1. A review of the values of impedance of the circuit consisting of trolley and track, and a method for calculating the same.

2. Several suggestions as to the methods of constructing current and power curves for single-phase equipments.

3. A discussion as to the accuracy of the typical run curve in its application to the results to be met in the entire series of runs.

4. An indication that in some cases the use of motor generators with the single-phase alternating current system does not preclude its comparing favorably with the direct current system of 600 volts.

5. While no general conclusions may be drawn from individual cases in the substitution of electricity for steam, the indications in the road here described are that, on the basis of passenger traffic alone, the undertaking will prove a profitable one.

## DISCUSSION ON "FROM STEAM TO ELECTRICITY ON A SINGLE-TRACK ROAD." ATLANTIC CITY, N. J., JULY 1, 1908

**J. B. Whitehead:** This paper was suggested by some of the questions arising in undertaking to change a 30-mile, single-track road from steam to electricity. It is understood, of course, that every project of this nature must be considered in the light of the particular conditions involved, so that it is rather to the methods which have been followed in the present case than to the actual results and values which were finally adopted, that I ask attention.

**W. I. Slichter:** In the equipment of a single-phase railway system one of the most important points is the design of the conductor system, since there is not the synchronous converter to fall back upon as a booster to make up for any line losses by its compounding.

The drop in voltage in the rails with alternating current has been investigated by various persons, but as Mr. Whitehead has pointed out, there seems to be considerable difference in the results obtained. It is probable that these results differ because of the numerous conditions which enter with important effects into the phenomenon.

The drop in the rail varies with the perimeter of the rail, because it is a skin effect; it also varies with the chemical composition of the rail, which affects the permeability; with the bonding which affects the true or ohmic resistance of the circuit, and with the quantity of current in the rail, as this affects the permeability; and with the leakage of current to ground.

While the results of experimental tests will differ greatly on this account, conditions found in practice do not vary so greatly and we do get quite reliable and uniform values.

The general results of a series of tests made under operating conditions show that at 25 cycles the impedance drop in the rail itself is approximately eight times as great as the ohmic drop with direct current, that the power-factor of this drop is about 80 per cent. The impedance drop in the trolley is approximately 50 per cent greater than that with direct current. The result is that the total drop with alternating current is approximately twice as great per ampere as the drop with direct current.

An interesting feature of this voltage drop is that it has a power-factor greater than the power-factor of the input to the car at free running and less than that at starting, but more closely approximating the power-factor of free running. Thus under free-running conditions this drop is almost algebraically subtracted from the sub-station voltage.

At starting, when the input to the car has a value about twice that of free running, the drop is out of phase with the line voltage and is subtracted geometrically at a large angle, so that at starting there is a loss of voltage only about 50 per cent greater than that at free running, although the ratio of line current and actual voltage drops is as two to one.

**Wm. McClellan:** In regard to the choice of systems. Of the various systems proposed for electrification, none of us knows which one is going to be the best, if there is a best. I am perfectly willing to grant that there may be a heavy grade at some place where a 1200-volt, direct-current system may seem the best; there may be a long grade, perhaps, where a three-phase system may seem very advantageous; there are other places where the 11,000-volt, single-phase system may seem the right one; and still other places where the 650-volt system may seem best; and so on.

But we are not electrifying heavy grades or tunnels. We are not electrifying small portions of systems. We are beginning to electrify whole systems. Therefore, while we cannot at present choose any one system and electrify by means of that system, yet we must constantly realize that the great problem we have is the electrification of the large system. If we are called upon to work with a tunnel or grade, or something which needs immediate electrification, let us keep in mind the whole problem of the general electrification of the whole road at some future day.

I know of one place where they want to make a forty-mile extension on a part of the system, where a certain system of electrification is used on the original part of the road. There is no question whatever that another system of electric propulsion is more advisable for the extension; the problem is to know what to do, whether to throw away the part now in use, and remake it, or go ahead with the old system and install that on the extension, which is the easier thing to do, and trust to the future.

It is fortunate that one large system decided to solve their problem on a general basis. As a result they have been subjected to criticism, because some one can show where a few dollars might have been saved now by adopting some other system. They have done wisely, however, in keeping in mind the electrification of the whole system rather than to adopt the method that is perhaps more immediately applicable.

**A. H. Babcock:** The method given herein is not the only accepted one to be followed in discussing problems of this character. If it were the only method, in at least one case with which I have to deal, we would be hopelessly at sea. That particular case involves the electrification of about 135 miles of trans-continental railroad over the Sierra Nevadas, with a grade rising 7,000 ft. in 83 miles.

Have there been any tests made on the road, as in operation, to show how much drop was encountered in the rails and in the overhead system, as compared with the calculated figures?

**J. B. Whitehead:** There have been no tests of these figures. The best I was able to do was to take the literature as I found it in the matter and lay the system out. The starting conditions are excellent, so far as I can observe. As for actual figures of drop, I have not been able to get any.

**A. W. Copley** (by letter): The subject of the constants of alternating-current railway circuits is one to which I have given considerable attention. During the last few years I have had opportunity to make a number of tests for the determination of such constants, the most important of which were made on the New York, New Haven & Hartford Railroad, under the general direction of C. F. Scott and W. S. Murray. The data obtained in these tests is summarized in the following tables. The values given for double-track and single-track are calculated from the data obtained on the four-track road; the values obtained in this manner for single-track check closely with the results of tests made elsewhere on single-track roads.

The impedances given in the table are the electromotive forces required for sending current through the circuit, and are practically equal to the difference between the electromotive forces at the power house and at the load. The values in the table are the volts required per mile per hundred amperes in the trolley.

The figures showing the division of current between the track and the earth refer to intermediate portions of long sections; the division is different near the power house and near the load.

The figures in the tables apply to average practical conditions and are suitable for the calculation of commercial circuits.

FOUR-TRACK ROAD

Four 0000 trolley wires........ Eight 100-lb. rails.

| Electromotive force............ | 25 cycles | 15 cycles |
|---|---|---|
| Resistance | | |
| Trolley.................... | 6.8 volts | 6.7 volts |
| Rail...................... | 1.8 " | 1.5 " |
| Total.................... | 8.6 " | 8.2 " |
| Reactance | | |
| Trolley wires (internal)..... | 0.35 | 0.2 |
| Rails (internal)............ | 0.85 | 0.5 |
| Between trolley and return circuit.................. | 15.6 | 9.4 |
| Total.................... | 16.8 | 10.1 |
| Impedance, total......... | 18.9 | 13. |
| Division of current | | |
| Each outside trolley wire..... | 26.6 amperes | 26.3 amperes |
| Each inside trolley wire....... | 23.4 " | 23.7 " |
| Rails...................... | 75 " | |
| Earth...................... | 25 " | |

FOUR TRACK WITH AUXILIARY FEEDERS

Four 0000 trolley wires.........Two 00 feeders Eight 100-lb. rails

| Electromotive force............ | 25 cycles | 15 cycles |
|---|---|---|
| Resistance | | |
| Overhead wires............ | 5.7 volts | 5.6 volts |
| Rail...................... | 1.8 " | 1.5 " |
| Total.................... | 7.5 " | 7.1 " |

| | | |
|---|---|---|
| Reactance | | |
| Overhead wires (internal) | 0.2 | 0.1 |
| Rails (internal) | 0.9 | 0.6 |
| Between overhead wires and return circuit | 13.3 | 8.0 |
| Total | 14.4 volts | 8.7 volts |
| Impedance, total | 16.5 “ | 11.2 “ |
| Division of current | | |
| Each feeder wire | 14.2 amperes | |
| Each outside trolley | 18.8 “ | |
| Each inside trolley | 17. “ | |
| Rails | 75 “ | |
| Earth | 25 “ | |

### Double-Track Road

| | | |
|---|---|---|
| Two 0000 trolley wires | Four 100-lb. rails | |
| Electromotive force | 25 cycles | 15 cycles |
| Resistance | | |
| Trolley | 13 volts | 13 volts |
| Rail | 2.5 “ | 2 “ |
| Total | 15.5 “ | 15 “ |
| Reactance | | |
| Trolley wires (internal) | 0.6 | 0.4 |
| Rails (internal) | 1.2 | 0.7 |
| Between trolley wires and return circuit | 25.1 | 15 |
| Total | 26.9 | 16.1 |
| Impedance, total | 31. | 22. |
| Division of current | | |
| Rails | 58 amperes | |
| Earth | 42 “ | |

### Single-Track Road

| | | |
|---|---|---|
| One 0000 trolley wire | Two 100-lb. rails | |
| Electromotive force | 25 cycles | 15 cycles |
| Resistance | | |
| Trolley | 26 volts | 26 volts |
| Rail | 3 “ | 2 “ |
| Total | 29 “ | 28 “ |
| Reactance | | |
| Trolley wire (internal) | 1.3 volts | .8 volts |
| Rails (internal) | 1.5 “ | .9 “ |
| Between trolley and return circuit | 44.2 “ | 26.5 “ |
| Total | 47. “ | 28.2 “ |
| Impedance, total | 55.3 “ | 39.6 “ |
| Division of current | | |
| Rails | 40 amperes | |
| Earth | 60 “ | |

Note.—With 000 trolley wire instead of 0000 for single-track the total impedance in volts per 100 amperes per mile is 60.

The earth losses are left out of the above tables. Such losses are comparatively small and are not easily measured; moreover they undoubtedly vary greatly with different kinds of soil and the ballast of the roadbed, the largest part of the loss occurring in the region where the current is leaking from the rails and going into the earth.

Mr. Whitehead has given figures for various losses in railway circuits published by Parshall & Hobart and by the Railway Test Commission and has made calculations of such constants from theoretical considerations. A comparison of the values given in his paper with values obtained from the tests on the New Haven road brings out several interesting points.

*Rail impedance.* The values for the ratio between the impedance of the rails at 25 cycles and the direct-current resistance, are given from Parshall & Hobart as 8.1 and from the Test Commission Report as 5.5. These ratios are presumably for an 80-lb. rail. Measurements made on the New York, New Haven & Hartford Railroad with 100-lb. rails with 0000 bonds gave a value of between 2.5 and 3 for the ratio. This ratio was obtained with current densities of from 40 to 200 amperes per rail, and the results show only a very slight increase in the ratio with increased density. The resistance of the rail showed no noticeable change with the density, but the impedance rose slightly as the density increased.

*Rail resistance.* The resistance of the rails to alternating current at 25 cycles as measured on the New Haven road was 0.16 ohm per mile of single rails. Multiplying this by the rail current gives the ohmic drop of voltage in the rails. With 100 amperes per rail, this would amount to 16 volts. This value is little more than half of the value given by the Railway Test Commission (28.8 volts for 80-lb. rail) which is used in Mr. Whitehead's calculations.

*Rail reactance.* The reactance within the rail was found in the New Haven tests to be about 8 volts per 100 amperes per mile for a single rail. The value used by Mr. Whitehead (21 volts for 80-lb. rail) in his calculations is that taken from the Railway Test Commission's tests and is over double the value given above for a 100-lb. rail.

*Rail current.* The proportion of the trolley current which returns by rails is seen from the tables to vary according to the number of tracks. A single-track road has only 40 per cent of the current returning by the rails while a four-track road has 75 per cent.

At the point where current enters the rails on a single-track road 70 per cent of the current starts toward the power house and 30 per cent in the opposite direction. The 30 per cent leaks from the rails into the earth in from two to three miles. Coming toward the power house the 70 per cent decreases to 40 per cent in about the same distance, and the rail current then stays at this value until near the power house. Similar results were found on the four-track road, 87 per cent starting toward the power house and decreasing to 75 per cent in two miles.

*Position of earth current.* The position of the earth current varies, no doubt, under different conditions of soil etc. On the New Haven road it was found that if the earth conductor was assumed as 1000 ft. in diameter and tangent to the surface at the rails, the constants of the circuit calculated theoretically would be substantially the same as those determined experimentally. For a single-track road an assumed diameter of 600 ft. gave theoretical constants the same as the measured values.

*Impedance volts due to trolley current.* In the calculation given for the division of current between a 000 copper trolley wire and a $\frac{7}{16}$ in. steel messenger wire, it does not appear that any allowance has been made in the value of $R_1$ (the resistance of the messenger wire) for the fact that the current is alternating. The value 3.7 ohms is about the value of the resistance to direct current, but 9 or 10 ohms is probably nearer the value for the resistance at 25 cycles. By making this change from 3.7 to 10, the values of $i_2$ and $i_1$ (the currents in the trolley wire and messenger respectively) become 97 and 3.5 amperes, respectively and $E$ (the impedance voltage in the circuit due to the trolley current) becomes 47.2 instead of 44.75. This value of $E$ (47.2 volts) is close to the value found by neglecting the messenger wire as a conductor.

*Impedance volts due to rail current.* The resistance voltage due to rail current as given above is 16.2 per 100 amperes in each rail per mile of 8.1 volts per 100 amperes in a pair of rails per mile.

The reactance volts due to the field inside the rails is 4 volts per mile of single track (two rails). The reactance voltage in the trolley-rail circuit due to rail current is calculated from the distance between rails and trolley wire, the rail current, and the diameter of the rails. If this last is taken as 2.5 in., the value of reactance volts is about 32 as is given by Mr. Whitehead for 100 amperes in each rail or 16 for 100 amperes in the track. The total impedance due to track current of 100 amperes is then $8.1 - j\,20$. Adding this to the value deduced for the impedance due to the trolley current, gives $E_0$, the total impedance, as 67.8 volts per mile per 100 amperes for 000 trolley wire and 100 lb. rails. Taking into account that the rail current is only 40 per cent of the trolley current drops the value of $E_0$ to about 60 volts.

**Chas. F. Scott:** Mr. Copley is, I believe, substantially correct in his measurements, and what he has contributed is a valuable addition to our knowledge on this subject. I might add that the height of the trolley wire is 22 ft.

**J. B. Whitehead:** I am particularly glad to see these figures. This is one of the objects which I had in mind in bringing the calculation of the impedance volts into the paper. I have only seen Mr. Copley's figures for the first time, in the last few minutes, and am not prepared to make specific comments upon them.

The value of the impedance volts for the single-track road is what I was most concerned with in my paper. I notice that the total impedance in Mr. Copley's discussion at 100 amperes per mile, is 60 volts as against 65 volts given in my paper.

The difference between 80 and 100 lb. rails at 100 amperes per mile is appreciable; maybe it will make up for the difference in impedance values.

I did not mention the matter of rail impedance at the time I was abstracting the paper, but I called attention at the time to the difference in the ratios of impedance of rails and direct-current resistances, as given by the several authorities which I quoted. I brought out in the substance of the paper the point which Mr. Copley has reported here. He has touched on the subject of rail resistance, and I would be glad to see more figures on that particular point. They are all over the place, if one looks up the measurements which have been taken, and doubtless the variations are caused by the different conditions of track under which the measurements are taken; that is the only way I can account for them.

As to the matter of rail current, these are the first figures I have seen bearing on the subject. I should like to ask Mr. Scott whether there were any single-track measurements taken at the time of these tests? Do I understand these figures for single-track are calculated from the results of four-track tests?

**Chas. F. Scott:** Yes; calculated, and also the result of direct measurement. The figures relating to three single-track measurements taken at three places are from actual tests.

**J. B. Whitehead:** I should like to see the record of these single-track tests, because there are remarkably few at present available in the literature. The resistance of the catenary cable at 25 cycles is placed here at from 9 to 10 ohms, but by conjecture only. The value appears excessive.

**S. H. Clarkson:** In figuring out the cost per car-mile, I should like to know whether Mr. Whitehead took the locomotive into consideration, and if so to what extent? It seems to me that the cost per ton-mile would be a much more equitable basis for comparison, not only in the present instance where a steam and a single-phase road are being considered, but in all cases where it may be necessary to compare trains having different equipment or motive power.

**J. B. Whitehead:** I shall answer the question last asked. The figures given at the end of the paper on the relative costs of operation are based entirely on the passenger traffic of the road. The freight traffic will be handled by steam, certainly for the present. The comparison here given is entirely on the basis of passenger traffic, and it has been estimated that a certain car mileage was necessary to handle the passenger traffic. That is the reason for the basis of car-mileage.

As to the maintenance of locomotives, the figures for the cost of maintenance are at once available from the company's books, and it was a simple matter to put them on the car-mileage basis.

*A paper to be presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 1, 1908.*

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# INDUCTION MOTORS FOR MULTISPEED SERVICE WITH PARTICULAR REFERENCE TO CASCADE OPERATION

BY H. C. SPECHT

During the last ten or fifteen years a great deal of work has been done toward perfecting methods for varying the speed of induction motors. Each of these methods has certain disadvantages, which have precluded the general adoption of any one of them for practical use. The method most generally applied for varying the speed is that of inserting resistance in the secondary circuit. This method of speed regulation, however, has the one great disadvantage that, for a certain load and speed a certain amount of resistance is required; and as soon as the load changes, the resistance must be changed in order to maintain the same speed. When the load is taken off the motor will return to its synchronous speed. It is also evident that such speed regulation can be obtained only by a great sacrifice of efficiency, due to the high ohmic losses in the secondary circuit.

For work which does not require large size motors, the above method might be satisfactory. For motors of large size, there are as a rule only two or three different speeds required; in such cases good efficiency and power-factor, and a good speed regulation for all loads and speeds are wanted. Motors which fulfil these conditions and which are best known are the following:

1. Independent motors with different numbers of poles, the rotors of which are mounted on the same shaft.
2. A single motor with separate windings, each of which is connected for a certain number of poles.

3. A single motor with one winding, which can be connected for different number of poles.

4. An induction motor, the secondary of which is connected to a synchronous motor.

5. Two induction motors connected either in direct or in differential concatenation or as single motors.

It is the intention in this paper to discuss mainly the characteristics and the operation of motor sets as mentioned in the last paragraph.

The motors of the cascade set are ordinary induction motors with wound secondaries, the rotors of both motors being mounted on the same shaft or interconnected mechanically by other means. The primary of the first motor is connected to the line circuit and its secondary winding to the primary winding of the second motor, which may be the stator or the rotor. The secondary of this last motor is short-circuited direct or through an external resistance.

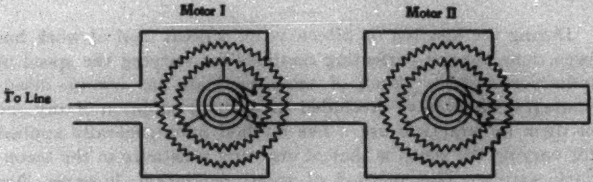

FIG. 1.—Concatenation diagram of motors arranged in direct concatenation

The two motors are connected in direct concatenation if they have a tendency to start up in the same direction, the synchronous speed being then $=\frac{\text{cycles}\times 120}{p_1+p_2}$, where $p_1$ is the number of poles of motor I and $p_2$ the number of poles of motor II. (See Fig. 1).

When the two motors tend to start in directions opposite to each other, they are connected in differential concatenation and have a synchronous speed of $\frac{\text{cycles}\times 120}{p_1-p_2}$ (Fig. 2).

We shall first investigate the changes of slip, frequencies, voltages, and magnetizing current in each motor when they are connected either in direct or differential concatenation and running at different speeds.

### NOTATIONS

$n_1$ = Synchronous speed of motor I, running as single motor.
$n_2$ = Synchronous speed of motor II, running on secondary circuit of motor I.
$n$ = Speed of the motor set.
$c_1$ = Frequency in the line circuit.
$c_2$ = Frequency in secondary of motor I and primary of motor II.
$c_2'$ = Frequency in secondary of motor II.
$e_1$ = Voltage on primary of motor I.
$e_2$ = Voltage induced in secondary of motor I.
$e_2'$ = Voltage induced in secondary of motor II.
$p_1$ = Number of poles in motor I.

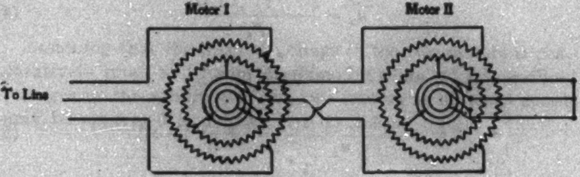

FIG. 2.—Concatenation diagram of motors arranged in differential concatenation

$p_2$ = Number of poles in motor II.
$t_1$ = Winding turns in primary of motor I.
$t_2$ = Winding turns in secondary of motor I.
$t_1'$ = Winding turns in primary of motor II.
$t_2'$ = Winding turns in secondary of motor II.
$s_1$ = Slip of motor I.
$s_2$ = Slip of motor II.
$s$ = Slip of motor set.

The slips of motor I and motor II may be expressed by:

$$s_1 = \frac{n_1 - n}{n_1} = 1 - \frac{n}{n_1} \qquad (1)$$

$$s_2 = \frac{n_2 \mp n}{n_2} = 1 \mp \frac{n}{n_2} \qquad (2)$$

The minus sign in the last equation is to be used when motors are connected in direct concatenation and the plus sign when motors are connected in differential concatenation.

The synchronous speeds of motor I and motor II may be determined from

$$n_1 = \frac{c_1 \times 120}{p_1} \tag{3}$$

$$n_2 = \frac{c_2 \times 120}{p}$$

In the latter formula the frequency ($c_2$) in the primary of motor II is equal to $c_1 s_1$ and $n_2$ may then be expressed by:

$$n_2 = \frac{c_1 \,.\, s_1 \,.\, 120}{p_2} \tag{4}$$

Formulas (1) and (2) combined, give

$$s_2 = \frac{n_2 \mp n_1 \, (1-s_1)}{n_2} = 1 \mp \frac{n_1}{n_2} (1-s_1) \tag{5}$$

Formulas (3) and (4) combined, give

$$\frac{n_1}{n_2} = \frac{1}{s_1} \,.\, \frac{p_2}{p_1}$$

and this latter equation placed into formula (5) gives

$$s_2 = 1 \mp \frac{1-s_1}{s_1} \,.\, \frac{p_2}{p_1} \tag{6}$$

or

$$s_1 = \frac{1}{1 \mp (s_2-1) \frac{p_1}{p_2}} \tag{7}$$

These last two equations, (6) and (7), show how the slip of one motor depends on the slip of the other motor. If, for instance, the slip of motor I equals 1, the slip of motor II will also equal 1; if $s_1 = 0$ then $s_2$ will equal infinity.

Since the primary of motor II is connected to the secondary of motor I, the frequency in both these members is the same, and equals:

$$c_2 = s_1 \, c_1 \tag{8}$$

The frequency in the secondary of motor II is

$$c_2' = s_2 \, c_2 = s_1 \, s_2 \, c_1$$

Replacing $s_2$ by its value in formula (6), we obtain

$$c_2' = s_1 \, c_1 \left(1 \mp \frac{1-s_1}{s_1} \cdot \frac{p_2}{p_1}\right)$$

or

$$c_2' = c_1 \left[s_1 \mp (1-s_1) \frac{p_2}{p_1}\right] \tag{9}$$

Assuming that the drop of voltage in the two motors is comparatively small and may, therefore, be neglected, the induced voltages in the windings of the two motors at different speeds may be expressed as follows:

$$e_2 = s_1 \cdot \frac{t_2}{t_1} \cdot e_1 \tag{10}$$

$$e_2' = s_2 \cdot \frac{t_2'}{t_1'} \cdot e_2 = s_1 \, s_2 \cdot \frac{t_2}{t_1} \cdot \frac{t_2'}{t_1'} \cdot e_1$$

The value of $s_2$ from formula (6) inserted, gives

$$e_2' = \frac{t_2}{t_1} \cdot \frac{t_2'}{t_1'} \cdot s_1 \cdot \left(1 \mp \frac{1-s_1}{s_1} \cdot \frac{p_2}{p_1}\right) \cdot e$$

or

$$e_2' = \frac{t_2}{t_1} \cdot \frac{t_2'}{t_1'} \cdot \left[s_1 \mp (1-s_1) \frac{p_2}{p_1}\right] \cdot e_1 \tag{11}$$

The above equations, (10) and (11), give the values of $e_2$ and $e_2'$. To obtain the exact values of the voltages $e_2$ and $e_2'$, it would be necessary to know the magnitude as well as the direction of the current vectors in the different members and the ohmic as well as the inductive resistance of the windings. This would mean a simple geometrical summation of voltages.

Let us now ascertain how the magnetizing currents change with the speed. When motor I is running as a single motor, the line circuit has to excite this motor only, and as is generally known, the magnetizing current for a given motor will be constant if the induced voltage and frequency remain constant, independent of the speed. Since in direct or differential concatenation the second motor is connected to the first, the line circuit must also furnish the exciting current for this second motor. From formulas, (8) and (10), we know that the induced voltage in the secondary of motor I (which at the same time is the voltage on the primary of motor II) changes in the same ratio as the frequency, the drop in the windings being ignored as before. Under no-load condition, to neglect this drop will not lead to any appreciable error.

Since the voltage $e_2$, on the primary of motor II changes directly with the frequency $c_2$, the magnetizing or no-load current in this motor will also remain constant at the different speeds. The exception to this is, that when motor I is running at its synchronous speed, the frequency and voltage of the primary of motor II become zero, with the result that the magnetizing current also becomes zero. And, as the vectors of the magnetizing currents of the two motors are practically in the same phase, they may be added numerically after being reduced to equal voltage. This sum would represent the total magnetizing or no-load current, and would be the same whether motors were connected in direct or differential concatenation.

To prove the correctness of the above formulas, tests as follows could be made:

### (A) MOTORS CONNECTED IN DIRECT CONCATENATION

Secondary of the second motor open-circuited, and the set driven mechanically by a third motor of variable speed characteristics. At different speeds the frequencies, voltages, and amperes to be taken in all members, the voltage and frequency on the primary of motor I to be held constant.

*Example of actual test and calculation.* Both motors wound 3-phase, of which motor I was designed for 8 poles, 50 cycles, 400 volts and motor II for 4 poles, 16⅔ cycles. 77 volts. The ratio of turns in motor I was

$$\frac{t_2}{t_1} = 0.58$$

and that of motor II was

$$\frac{t_2'}{t_1'} = 0.66.$$

Fig. 3 represents the different values when motors are connected in direct concatenation. These values are derived from the previous formulas and have been proved by actual test.

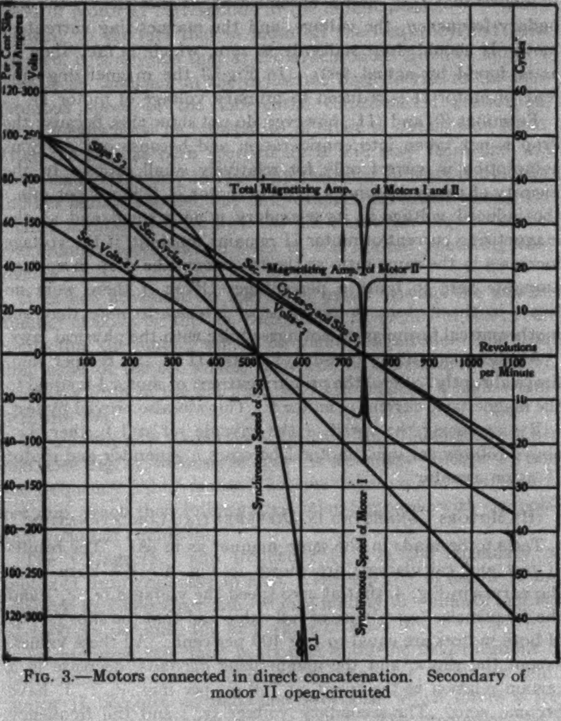

FIG. 3.—Motors connected in direct concatenation. Secondary of motor II open-circuited

The conditions at zero speed are practically identical with those of a stationary transformer connected in cascade. With increase of speed the induced secondary voltages ($e_2$; $e_2'$) and the frequencies ($c_2$; $c_2'$), of motors I and II, the slip ($s_1$) of motor I and slip ($s_2$) of motor II decrease. At the synchronous speed of the cascade set (500 rev.per min.) $e_2'$, $c_2'$, and $s_2$ drop to zero and above that speed they become negative, which indicates that motor II acts as an induction generator.

At 750 rev.per min., motor I reaches its synchronous speed and it follows that $e_2$, $c_2$, and $s_1$ become zero. Consequently the secondary frequency, the voltage, and the magnetizing current of motor II should drop suddenly to zero, which, in fact, they do as is found by actual test. (In Fig. 3 the magnetizing current of motor II is reduced to primary voltage of motor I).

Formulas (9) and (11), however, do not show this, because the drop is not taken into consideration and because our previous assumption is correct only for relatively small drops. In the vicinity of the synchronous speed of motor I, (750 rev.per min.) the induced voltage in its secondary is very small and as the magnetizing current of motor II remains constant, if the voltage increases in the same ratio as the frequency, the drop in voltage amounts here to quite a percentage. Even if there were no losses in the motors, it might be of interest to note that our mathematical formulas do not agree fully with the physical laws.

As the magnetizing current of motor II at 750 rev.per min. drops abruptly to zero, the primary current of motor I is equal to the magnetizing current of motor I. This was also proved by test.

By increasing the speed of the cascade set still further, *i.e.*, above 750 rev.per min., motor I becomes a generator and motor II again a motor.

### (B) MOTORS CONNECTED IN DIFFERENTIAL CONCATENATION

Tests to be made in the same manner as in (A). The results of test and calculations are shown in Fig. 4. We learn from the curves in Fig. 4, that at zero speed the voltages ($e_2$; $e_2'$) and the frequencies ($c_2$; $c_2'$) are of full value and that the slips ($s_1$; $s_2$) of both motors are equal to 1 or 100 per cent. All these values, except the slip $s_2$ and the magnetizing currents, decrease in a certain relation to the speed; at 750 rev.per min., $e_2$, $c_1$, $s_1$ have become zero. The secondary voltage ($e_2'$) and the frequency ($c_2'$) at this speed drop abruptly from half their full values to zero, owing to the zero voltage and frequency in the primary of motor II.

The slip ($s_2$) of motor II increases from 1, slowly at first, but gradually faster and faster until infinity. Taking into consideration the several rotations of the fields as well as data given above, we find that up to this speed, 750 rev.per min., both machines act as motors. At 750 rev.per min., motor I runs at its synchronous speed; and since the cycles in the primary of motor II have dropped to zero and further, since motor II formerly ran in the direction opposite to its normal rotation, the speed of motor II corresponds to the infinite value.

Owing to the fact that in motor II the frequency and volts are zero, it is obvious that at the synchronous speed of motor I there is no tendency in the motor set itself to rise to the synchronous speed of the differential concatenated connection. Other means must be resorted to in order to obtain this speed. After the set has been speeded up it will stay there and will carry load. One way to speed up the set is to start it by using another motor; another way is to connect the motor having the smaller number of poles with the line and when the set reaches synchronous speed switch over to the normal operating connection.

It is not advisable to leave the motor having the smaller number of poles on the line because the frequency in the circuit connecting the motors will be of double magnitude. The total iron losses of the set would, therefore, be considerably greater, causing a drop in the efficiency and also causing a higher temperature rise.

Considering now the curves of the pass from 750 to 1500 rev.per min. (see Fig. 4), we observe that the secondary voltage ($e_2$) and the frequency ($c_2$) of motor I become negative and at 1500 rev. per min. reach their full negative value compared with the positive values at standstill.

The voltage ($e_2'$) and frequency ($c_2'$) in the secondary of motor II drop gradually to zero. The slip ($s_2$) of motor II has changed at 750 rev.per min. from +infinity to –infinity and has at 1500 rev.per min. the final value of zero.

In reviewing this data, bearing in mind the field rotations in both motors, we observe that at a speed above 750 rev.per min., motor II becomes an induction generator which forces a frequency into the secondary of motor I. This frequency has a field rotation opposite to that of the primary of motor I. The result is that the rotor of motor I must run at a speed corresponding to the sum of the primary and secondary frequencies ($c_1$ and $c_2$) in order to be in synchronism.

Since the primary voltage ($e_3$) of motor II varies directly with its frequency ($c_{s_2}$) the magnetizing current of motor II remains constant, ignoring the drop in the windings.

At 750 rev.per min., however, the magnetizing current of this motor will suddenly drop to zero owing to absence of voltage and frequency. As the magnetizing current of motor I is constant and has practically the same power factor as the magnetizing current of motor II, these currents can be added numerically (when reduced to the same voltage as is done in Fig. 4), to get the total magnetizing current of the set. This current will be the same as in direct concatenation.

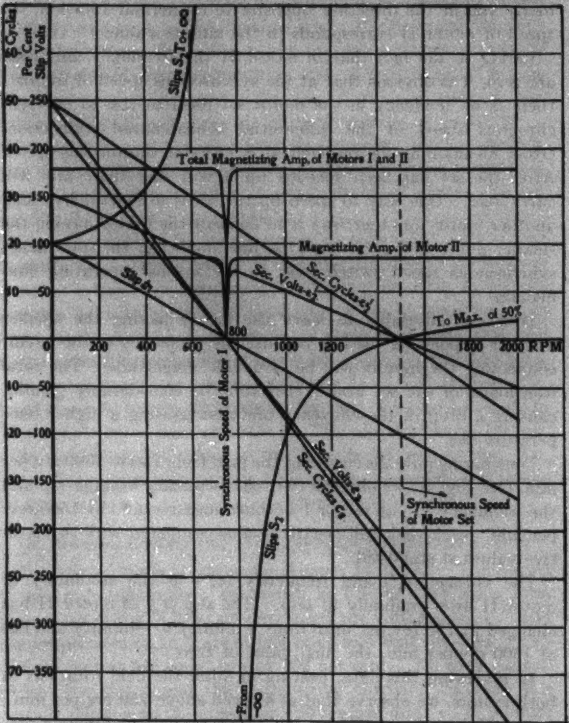

Fig. 4.—Motors connected in differential concatenation. Secondary of motor II open-circuited

*Conditions with secondary of motor II closed.* In the foregoing it has been shown that with motors connected either in direct or differential concatenation, running at their synchronous speed, the frequency and voltage in the secondary winding of motor II is zero. Therefore, the short-circuiting of this winding would not affect conditions in the other members. When the motor set is running on load the speed will be somewhat lower. In each winding there will be a certain frequency and voltage and, therefore, some current. The voltages, magnetizing amperes, and frequencies of all members may be taken from Figs. 3 and 4 respectively, and by taking into consideration the drop in the winding, it is possible to determine the actual currents which flow. The primary current ($i_1$) in motor I is made up of its magnetizing current ($i_{01}$) and its secondary current ($i_2$) which form a triangle. The secondary current of this motor is at the same time the primary current of motor II and this current again is made up of the magnetizing current ($i_{02}$) and secondary current ($i_2'$) of motor II, which also form a triangle. (See Fig. 5.)

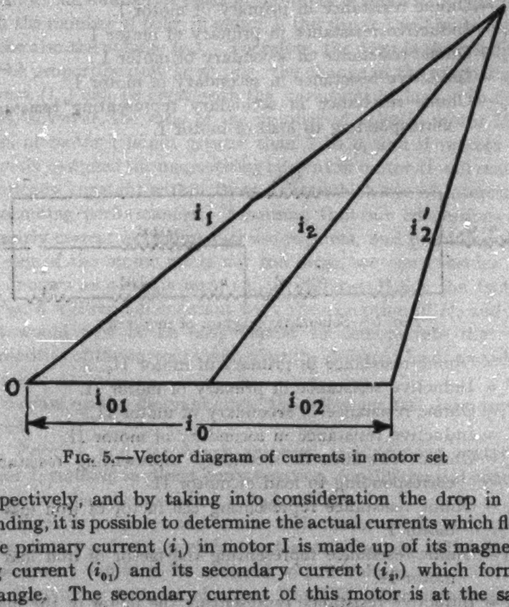

FIG. 5.—Vector diagram of currents in motor set

The two vectors of the magnetizing current ($i_{01}$) and ($i_{02}$) are practically in line as mentioned before.

The inductive resistances and the corresponding induced voltages vary directly with the frequency, the ohmic resistances being generally small in comparison with the inductive resistances. Therefore, considering the voltages as constant, the inductive resistances, according to this theory, must also be considered constant. An induction motor is equivalent to a circuit with ohmic and inductive resistances, providing the winding turns are reduced to the same voltage. To a certain extent, this is also true of a motor set connected either in direct or differential concatenation as shown in Fig. 6.

In the above:

$r_1$ = Ohmic resistance in primary of motor I.
$x_1$ = Inductive resistance in primary of motor I
$r_2$ = Ohmic resistance in secondary of motor I.
$x_2$ = Inductive resistance in secondary of motor I.
$R_1$ = Ohmic resistance in secondary representing resistance corresponding to load of motor I.

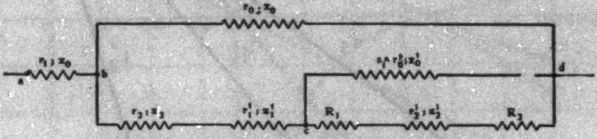

Fig. 6.—Schematic diagram of motor set

$r_1'$ = Ohmic resistance in primary of motor II.
$x_1'$ = Inductive resistance in primary of motor II.
$r_2'$ = Ohmic resistance in secondary of motor II.
$x_2'$ = Inductive resistance in secondary of motor II.
$R_2$ = Ohmic resistance in secondary representing resistance corresponding to load of motor II.
$r_0$ = Ohmic resistance representing the factor of iron loss in motor I.
$s_1 r_0'$ = Ohmic resistance representing the factor of iron loss in motor II.
$x_0$ = Inductive resistance representing the factor of the magnetizing current in motor I.
$x_0'$ = Inductive resistance representing the factor of the magnetizing current in motor II.

In Fig. 6 everything remains constant except $s_1'$ $r_0'$, $R_1$ and $R_2$. The resistance representing iron loss in motor II varies directly with the slip of motor I approximately. $R_1$ and $R_2$ vary inversely with the slip ($s$) of the set approximately.

It is apparent in Fig. 6, that with increase of load or increase of amperes, the voltage across the points ($c\ d$) decreases on account of the drop in voltage in the section ($a\ c$). This results in a decrease of magnetizing current in motor II. The question now is, what will this change amount to. According to formula (10), the voltage ($e_2$) of the secondary of motor I, (which is also the primary voltage of motor II), depends mainly on the slip ($s_1$) of motor I and this slip depends in turn on the ratio of the number of poles in both motors and on slip ($s_2$) of motor II. If for instance, the number of poles in motor II is small in comparison with the number of poles in motor I, the slip ($s_1$) will be small, as will be also the voltage ($e_2$). Therefore, the drop in the windings will be proportionately large ; *i.e.*, the change in the magnetizing current ($i_{02}$) will be great with the variations of load. In most cases, however, the ratio of the number of poles in motor II to those of motor I is not greater than 1 to 3, and if motors are properly designed the magnetizing current in motor II will remain practically constant within those limits which are of interest in determining performances. Assuming that our conclusions are as nearly correct as commercial use requires, and providing that the slip of the motor set is not too large, we can consider the two motors as a single one; *i.e.*, at different loads the factors in Fig. 6 will remain constant with the exception of $R_1$ and $R_2$.

It would now be an easy matter to demonstrate that the extremities of the current vectors for the different loads travel on a circle.[1]

To draw up the diagram circle the following test data are required:

1. Primary and secondary amperes and primary watts of motor I, running in direct concatenation (or differential concatenation as the case may be) at full voltage.
2. Primary amperes and watts with motor set locked, to be taken at any voltage, preferably at approximately half voltage, these tested values to be reduced to full voltage.
3. Secondary voltages of motor I and II, when standing still and secondary of motor II open-circuited.
4. Ohmic resistance of primary and secondary windings of

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[1] *Electrical World & Engineer*, Feb. 23, 1905, "Practical Diagram for Induction Motors."

motor I and of primary winding of motor II. All resistances to be reduced to the primary of motor I.

To show how the diagram circle is obtained from few test values and how the performances are derived from the same, the following example is made use of:

Motor I, 60 h.p., 400 volts, 50 cycles, 8 poles, primary as well as secondary wound, three-phase in star.

Motor II, 60 h.p., 77 volts, 16⅔ cycles, 4 poles, primary as well as secondary wound, three-phase in star.

These two motors were connected in direct concatenation, the primary of motor II being connected to the secondary of motor I, and the primary of motor I to a line circuit of three-phase, 400 volts, 50 cycles, and finally the secondary of motor II short-circuited.

### (1) No-Load Readings

$i_0$ = 71.4 amperes, total in primary of motor I.

$i_{0_2}$ = 34 amperes, total in secondary of motor I, reduced to primary winding.

$P_0$ = 3.1 kw. no-load losses.

### (2) Locked Readings

$i_L$ = 412 amperes in primary of motor I.

$P_L$ = 64.6 kw. in primary of motor I.

### (3) Motors at Rest, Secondary of Motor II Open-circuited

Voltage $e_2 = 232$ and $e_2' = 153$.

### (4) Resistance per leg Reduced to Primary Winding of Motor I and to a Temperature Corresponding to Continuous Full-Load Run

$r_1$ = 0.11 ohms in primary of motor I.

$r_2$ = 0.104 ohms in secondary of motor I.

$r_1'$ = 0.064 ohms in primary of motor II.

$r_2'$ = 0.046 ohms in secondary of motor II.

In Fig. 7, the vertical axis represents the direction of the voltage impressed into primary of motor I; the quadrant *A B* with its center *O* and with a radius of 100 parts represents the power-factor circle.

To determine the center of the diagram circle, first lay off to a convenient scale the no-load and locked current vectors

$$O\,C_0 = 71.4 \text{ amperes,}$$

and

$$O\,C_L = 412 \text{ amperes,}$$

in the direction of their respective power-factors.

$$\cos\phi_0 = \frac{P_0 - [i_0^2\, r_1 + i_{02}^2\,(r_2 + r_1')]}{i_0\ .\ e_1} = 0.0825$$

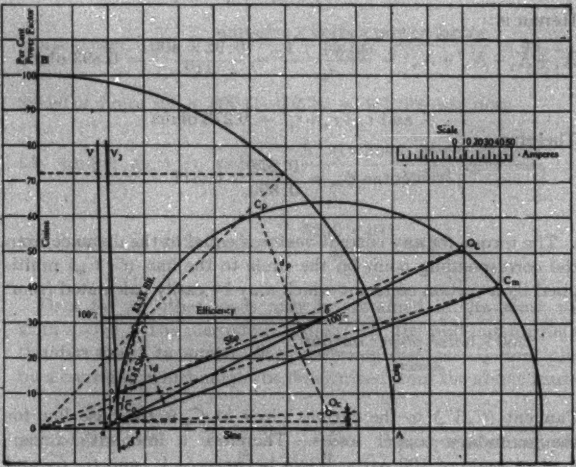
Per Cent Power Factor
B
100
90
80
70
60
50
40
30
20
10
0
Cosine
V
V₂
Scale
0 10 20 30 40 50
Amperes
C_p
d_p
O_L
C_m
83.5% Eff.
100%
Efficiency
C
δ
100%
Slip
1.8% Slip
d
O
C_0
O_c
a
Sine
A
Cos

Fig. 7.—Circle diagram

$$\cos\phi_L = \frac{P_L}{i_L\ .\ e_1} = 0.392$$

Then from $C_0$ draw the line $C_0\,O_c$ making an angle $\epsilon$ with the base line

$$\tan\epsilon = \frac{i_0\ r_1 + i_{02}\ (r_2 + r_1')}{e_1} = 0.0339$$

The intersection of the line perpendicular to the middle of $\overline{C_0 C_L}$ with the line $\overline{C_0 O_c}$ is the center of the diagram circle. The line $\overline{C_0 C_L}$ represents the base line for the output; *i.e.*, the distance from any point on the circle above $\overline{C_0 C_L}$ to this line $(\overline{C_0 C_L})$ multiplied by a certain constant gives the horse power output for the corresponding current vector.

The line which connects the points $C_0$ and $C_m$ represents the base line for torque; the point $C_0$ is already known and point $C_m$ can be determined by

$$\text{cotan } \phi_m = \frac{r_1 + r_2 + r_1'}{X_1 + X_2 + X_1' + X_2'}$$

Herein is:

$$X_1 + X_2 + X_1' + X_2' = \frac{\sin \phi_L \; . \; e_1}{i_L} = \frac{0.92 \times 400}{412} = 0.893 \text{ ohms}$$

$$\text{and } r_1 + r_2 + r_1' = 0.278 \text{ ohms}$$

Therefore:

$$\text{cotan } \phi_m = \frac{0.278}{0.893} = 0.311$$

The torque for any current vector is equal to the distance from the corresponding point on the circle to the line $(C_0 C_m)$ multiplied by a certain constant which may be easily calculated from:

$$\frac{5250 \times \text{horse power output}}{\text{speed}} = \text{lb. torque at 1 foot radius.}$$

Tangent $(C_0 V_2)$ to the current circle at $C_0$ is the base line for the secondary copper losses. Therefore a line with a convenient scale of 100 parts drawn between $\overline{C_0 V_2}$ and $\overline{C_0 C_L}$ and parallel with $\overline{(C_0 C_m)}$ gives the slip scale. A line from $C_0$ through any current point on the circle indicates the percentage of slip on the latter scale, reading from left to right.

A line $(a V)$ drawn through the intersection $(a)$ of line $\overline{C_0 C_L}$ with $\overline{O A}$ and which makes approximately an angle with $\overline{O A}$ equal to $\frac{1}{2}$ $(90° + < \delta)$, ($\delta$ being the angle of $\overline{V C_0}$ with $\overline{O A}$) represents the base line for the total losses. Therefore, a convenient scale between this line and $\overline{C_0 C_L}$ and parrallel to $\overline{O A}$ represents the efficiency scale, *i.e.*, a line from $(a)$ through any current point of the circle will indicate on the scale the percentage of efficiency. As an example Fig. 7 shows the results for point $C$ only, which are as follows:

$\overline{OC}$ = 124 amp. (total); efficiency = 83.3 per cent.; slip = 3.8 per cent.; power factor = 72 per cent. From these we calculate

$$\text{Horse power output} = \frac{\text{amperes} \times \text{volts} \times \text{efficiency} \times \text{power-factor}}{746}$$

$$\text{Horse power output} = \frac{124 \times 400 \times 0.833 \times 0.72}{746} = 40$$

$$\text{Horse power input} = \frac{\text{amperes} \times \text{volts} \times \text{power-factor}}{746} = 48.2$$

$$\text{Speed of motor set} = 500\ (1-0.038) = 481 \text{ rev. per min.}$$

$$\text{Lb. torque at 1 ft. radius} = \frac{5250 \times \text{horse power output}}{\text{speed}}$$

$$\text{Lb. torque at 1 ft. radius} = \frac{5250 \times 40}{481} = 437$$

Data for all other loads may be obtained in the same way as in above. The maximum torque; *i.e.*, the pull-out torque of the motor set, is equal to the maximum distance $d_p$ multiplied by a constant, which might be determined from the above load of

point $C$ constant $= \dfrac{\text{lb. torque}}{d} = \dfrac{437}{d}$. Consequently maximum

torque $= \dfrac{d_p}{d} \times 437 = 788$ lb. at 1 ft. radius.

All the data derived from this diagram checked up to within a fraction of 1 per cent. with the results obtained by test and by calculation.

In the same way as described above we may obtain the data for motors connected in differential concatenation.

Comparing now these results with those which might have been obtained from two independent motors, one having 12 poles and the other 8 poles, and together having the same amount of material as the complete cascade set, we find the following: The efficiency and power-factor will be somewhat higher if each motor has the same maximum torque as the cascade set. Nevertheless, the cascade set has certain advantages over a set composed of two independent motors. A few of the more important points of advantage are: greater latitude in design, a more flexible and a simpler speed control, and safer operation.

For instance, in a cascade set the individual motors may be designed so as to have greater width and smaller diameter, thus keeping the peripheral speed lower than would be the case with a single motor for the speed of direct concatenation. In cascade connection each motor tends to balance the other, consequently the speed regulation is more smooth; that is, the change from slow to high speed or from high to slow speed can be made gradually without any mechanical jarring or electrical choking effects. For example, a change from slow to high speed can be accomplished by inserting a high resistance across the circuits connecting motors I and II and then cutting out resistance gradually with the increase in speed until the set reaches the normal speed of motor I, or any other between that of synchronism of motor I and that of cascade connection as may be desired; all other connections to remain unchanged. In a case where three or four different speeds are wanted, it is obvious that a cascade set can be built very much more cheaply than three or four independent motors. For instance with two motors, motor I having 10 poles and motor II 6 poles and at a line frequency of 60 cycles, the following synchronous speeds can be obtained:

1. Motor 1 and II in direct concatenation 450 rev. per min.
2. Motor I runs single 720 rev. per min.
3. Motor II runs single 1200 rev. per min.
4. Motor I and II in differential concatenation 1800 rev. per min.

It should be noted that the above speeds are possible with a set consisting of a 10-pole motor and a 6-pole motor. Other combinations of speeds may, of course, be obtained by changing the number of poles. However, in any combination of motors the speeds have a certain arbitrary relation to each other. For this reason the four speeds obtained might in some cases not be the ones desired; that is, some of them could be the ones wanted while the others would not be.

In comparing the different methods of varying speeds of induction motors we find that each method has some advantage over the others when considered in connection with certain classes of work. But at the same time, there are certain disadvantages to be found in all these methods. The operation of a cascade set is simple and safe even if the efficiency and power factor are not altogether the best, on account of the increased inductance.

The elimination of this objection depends, it would seem, on the development of an efficient and practical phase compensator.

## DISCUSSION ON "INDUCTION MOTORS FOR MULTISPEED SERVICE WITH PARTICULAR REFERENCE TO CASCADE OPERATION."

ATLANTIC CITY, N. J., JULY 1, 1908

**W. I. Slichter:** There is a point in the subject of cascade connection of induction motors which the speaker would like to hear discussed, as it is particularly important in connection with railway engineering. The usual and first idea of the result of the cascade connection of induction motors is that it will make it possible to obtain from a given pair of motors a greater torque at a low speed than is obtained in normal operation. But a closer study of this subject shows that the maximum torque of two motors connected in cascade is always less than that of either one of the individual motors. This is a proved fact with regard to the operation of motors with like numbers of poles, but it would be interesting to know what the relation is with motors having different numbers of poles.

**A. E. Averrett:** I have found that, in general, concatenated coupling, when used for a very small range of speed, will work out quite nicely, as it is comparable to a relatively small change of voltage, with a compensator or autotransformer, but as the range of speed increases, the effectiveness of the concatenated set decreases. The second motor has all its power carried through the first motor, and the first motor will have a great impedance drop, so that the effective voltage of the second motor, after the current has passed through the impedance of the first motor, is low. Furthermore, the concatenated motor acts similarly to a single two-speed motor. The lower the speed of any induction motor, the lower the power-factor; that is, in case the speed reduction is by a change of poles. A constant-speed, collector-ring, induction motor will maintain approximately constant torque with an efficiency in proportion to the speed; a concatenated or multispeed motor, where the change of speed is made by shortening the pole pitch, will maintain fairly constant efficiency, but the power factor goes down with the speed reduction. In concatenated motors the problem is nearly as much a mechanical as an electrical problem; the diameters become small, distances between bearings centers increase, and with the slow speed which we are really trying to maintain, the question of ventilation becomes important. There was recently built a concatenated set for a very peculiar service, rolling mill work, where the concatenated motors were 20 and 16 poles, and the combination 36 poles. It happened that the power required for the actual concatenation work, at 36 poles, was very slight, the main power being at the 20- and 16-pole speeds.

Most motor work will require constant torque or perhaps torque increasing as the speed drops (constant power). In these cases, the low power-factor of the concatenated motor renders it extremely difficult to make a good combination at the low speed; but for a close range to the normal speed, as before stated, the concatenated motor works very well.

**Elmer A. Sperry:** Can anybody here throw light on the subject of returning power to the line when this class of motor is employed in traction service, coupled as described?

**H. C. Specht:** It has been asked if two motors connected in cascade would give any more torque than one of the motors. This certainly is not possible unless auxiliary devices are used. The motors connected in cascade will have somewhat less, or not more torque, than the average of the two motors, and the reason is simply that the current has to pass through both motors, which increases the leakage. As was mentioned at the end of my paper, it is a problem of finding a good phase compensator, to eliminate the most objectionable features of cascade connections.

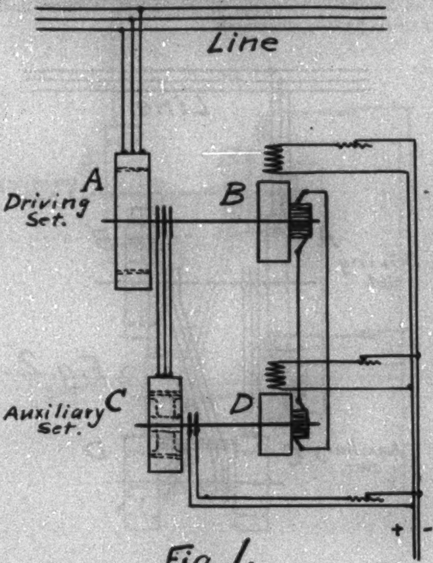

Fig. 1.

In regard to compensated cascade sets, I would like to mention that several schemes have been suggested in the last few years. Whether or not any of these schemes will be adopted for general use and give satisfactory results, is yet an open question.

The method generally used for compensation is that of connecting a synchronous motor or a compensator induction motor in the secondary circuit. The motors are then regulated so as to produce a leading current. Since this current, with the primary current and the magnetizing current of the main motor, form a triangle, it is possible to raise the power-factor not only to one but to obtain an over compensation or leading current.

The following will serve as examples of the methods referred to and as described recently by Heyland, Willner, and Kubler in German technical periodicals.

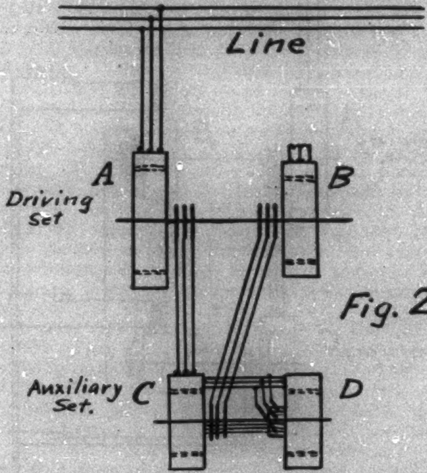

Fig. 2.

Fig. 1 shows an arrangement with a synchronous motor (*C*) in the secondary circuit. On the same shaft with the latter motor is a direct-current generator which supplies current to the second driving motor (*B*), which is, in this case, a direct-current motor. The direct-current machines and the synchronous motor are excited from a separate direct-current circuit.

In Fig. 2, compensation is accomplished by means of a compensated induction motor (*D*) connected to the secondary circuit of the main driving motor and to the other induction motor (*C*), which latter is mounted on the same shaft as the compensated motor, and serves as a frequency changer.

The second driving motor (*B*) is also an induction motor and is connected to the secondary circuit of motor (*C*).

In Fig. 3 is shown a method similar to that in Fig. 1, with the exception that the synchronous motor (*C*) is replaced by an induction motor, the secondary of which is connected through the collector rings to the armature winding of the driving motor (*B*).

The foregoing methods serve not only to compensate the power-factor, but also allow of starting up the tandem set with a great deal less kilowatt input than would be required in the case of ordinary induction motors, on which a great deal of power is wasted on the secondary resistance. It likewise increases the maximum running torque over that of an ordinary cascade set.

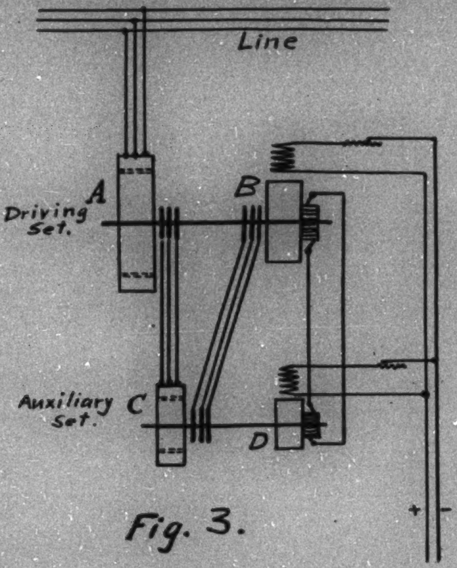

Fig. 3.

In addition, the schemes as shown in Figs. 2 and 3, permit of reversing the set in a comparatively short time and with no sudden rush of current, as the inertia in the two driving motors is kept small. The flywheel on the auxiliary motors serves as a storage for kinetic energy. For obvious reasons these latter should be designed for high speed.

Further, we see that the methods above described allow of running tandem sets at variable speeds with the minimum waste of energy. In some respects they are similar to the Ilgner & Leonard reversing systems.

The method as shown in Fig. 3 would seem to contain possibilities in connection with hoisting, rolling-mill, and traction service.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 1, 1908.*

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# THE DETERMINATION OF THE ECONOMIC LOCATION OF SUB-STATIONS IN ELECTRIC RAILWAYS

BY GERARD B. WERNER

The method of attacking the problem of the location of sub-stations in electric railways is governed by the physical layout of the road. The problem involved in the case of networks serving a limited territory, such as urban or suburban lines, may be solved from a study of the magnitude of the various relatively fixed load-centers which are created by the configuration of the lines; and the sub-stations may be placed at the different centroids of the system. In the case of long single roads connecting distant communities, such as interurban and trunk lines, there is presented the study of more or less uniformly loaded stretches, in which there are no distinct centers of load, except those that result from the characteristics of the line profile or the traffic movement. The latter problem is more susceptible to mathematical treatment, so that the contents of this paper will be confined to the consideration of interurban and trunk line projects, or, in other words, to relatively long roads.

Of the various considerations that govern the layout of the secondary distribution of electric railways, the question of economy is generally the preponderant influence. It is obvious that the economic condition should be determined as a basis of reference, and approximated as far as is consistent by the actual design. The theoretical economic solution, however, may be difficult or impossible of attainment, if certain operating considerations of a mechanical or an electrical nature intervene and dictate the use of a cross-section of secondary copper other than that determined by Kelvin's law. For example, the economic drop may exceed the limiting drop permitted for the acceleration of the motors, under which conditions economy would give precedence to regulation. In the present problem, as will appear shortly, for a given mean square current per car, a given cost of copper, and a given unit cost of energy, the drop, according to Kelvin's law, is inversely proportional to the square root of the number of annual car-hours. The cross-section of the secondary copper is, therefore, dependent on the number of cars or trains in service, the length of line, and the schedule speeds. Thus for infrequent service, the economic drop may be excessive and result in stalling the cars; similarly, for dense traffic movements, the economic drop may be insufficient and render the resulting investment prohibitive. Kelvin's law is based on the mean power lost, while the operating criterion is based on the maximum drop.

Besides these technical considerations, which may be decisive in the design of the distributing copper, a number of commercial considerations exert a pronounced influence on the location of the sub-stations. In this category may be included the question of placing the sub-station at or near a railway station, in order to utilize the station employes for emergency switchboard operation, or to provide accessibility for periodical inspection, in the absence of continuous attendance. Thus, the sub-station may be somewhat removed from the site determined by purely economic reasons.

The specific purpose of this paper is to develop an equation for the number of sub-stations, or the distance between sub-stations, which will render the total annual charges on the installation a minimum. This equation is to be in terms of the various constants fixed by the length of line, time-table, the weight of cars or trains, the motor characteristics, the cost of energy, and the equipment charges.

The initial step in the treatment of this problem is the determination of the analytical expressions of the various annual charges as functions of a single variable, the number of sub-stations. All those items of the annual charges which may be regarded as constant and independent of the number of sub-stations, may be omitted in the analysis. Thus, assuming that it is not necessary to feed the sub-stations with separate high-tension lines, the weight of copper and the losses in the primary distribution are dependent only on the energy to be transmitted and the mean distance, so that the primary transmission may be eliminated from consideration. Obviously, the charges on the trolley suspension and insulation do not enter. The following algebraic expressions are therefore required:

1. Annual charges on sub-stations,
2. Annual charges on overhead copper,
3. Annual cost of sub-station losses,
4. Annual cost of secondary conductor losses.

These four items are present whether the system employed is continuous, single-phase, or three-phase current. For the purposes of this paper, it will be sufficient to develop the formula for the simplest layout. The single-phase system has been elected, therefore, to illustrate the general method of deducing the equation, although by the introduction of the proper modifications in the analytical expressions (to cover such features as the third-rail, synchronous converters, attendance, etc., in the continuous-current system, and the two overhead conductors, three-phase transformation, etc., in the three-phase system) the results of this analysis will be equally applicable to all.

*Annual charges on sub-stations.* The first point to be determined is the sub-station capacity. In general, if a line contemplates electrification we may assume that the frequency of the various traffic movements dictated by the present or prospective time-table results in a more or less uniformly distributed load along the line, and consequently the load between adjacent sub-stations varies more or less directly with the length of the sub-station section. Thus, neglecting for the moment the question of reserve, the capacity of each sub-station will be proportional to the distance between sub-stations, the aggregate sub-station capacity remaining constant, and being governed by the total maximum load occurring on the line at one time.

In those classes of service where the traffic density through the varying exigencies of the train-weights, time-table, or profile, is not uniform along the entire line, it is necessary to consider individual *load-sections* rather than general *distance-sections*. When this condition exists, the line may be broken up into divisions where the load per mile is approximately constant, each particular division segregated, and treated separately for the determination of the sub-station capacity and the distance between sub-stations.

The question of spare capacity is influenced by the kind of transformation between the transmission and the distribution.

A three-phase primary may be incumbent on account of one or more of the following reasons: 1. The railroad may desire to sell surplus power to various industrial establishments where single-phase current is not acceptable. 2. The additional cost of single-phase generation may not offset the advantages accruing from the simplicity of the switching gear. 3. The railroad may, from compelling commercial reasons, desire to purchase its power from an outside company.

With a three-phase primary transmission we are practically limited to two methods of transformation to the secondary distribution. 1. Sub-stations transforming to single phase and feeding successive sections with separate phases, or 2, sub-stations transforming to two-phase and feeding adjacent sections with either phase. In the first case, two transformers are required in each sub-station, so that the same phase may be supplied to the common section extending between them. In the second case, two transformers are also required, so that the sub-station capacity will be divided between at least two units, with a possible third as a spare unit.

With the assumption made above of the uniformity of the distribution of load along the line either (*a*) for the entire stretch between terminal, or (*b*) for the particular load-section in question, and further assuming that the transformers are capable of withstanding momentary overloads of 150 per cent., the following expression results:

$$K\,W = \frac{0.4\,P\,(1+q)}{s} \tag{1}$$

where

$K\,W$ = required capacity of one sub-station in kilowatts,

$P$ = total maximum power input in kilowatts required at one time on the line,

$q$ = spare capacity in terms of the capacity actually required

$s$ = number of sub-stations

One transformer will have a capacity of

$$K\,W' = \frac{0.2\,P}{s} \tag{2}$$

The cost of a single sub-station consists of the cost of real estate (building and ground) which may be taken as independent of the capacity, and the cost of equipment, which is a function of the capacity. The equipment cost comprises the cost of transformers, switchboard, wiring and protective apparatus. The cost of the transformers for a given type, voltage and frequency in sizes between 150 kw. and 500 kw. may be taken as a linear function of the output as follows:

$$F_t = 2\,(K_1 + K_2\,K\,W')\,(1+q) \tag{3}$$

where $K_1$ and $K_2$ are constants fixed by the manufacturer.

The remainder of the equipment may be grouped as auxiliary, and, without appreciable error, taken at a fixed constant value irrespective of the kilowatt capacity. If it is further assumed that one average fixed charge will uniformly cover the different equipment items, and another the building and ground, the annual charges on the total sub-stations may be written down:

$$a_s = s\left[f_r\,F_r + f_e\left\{F_a + (1+q)\left(2\,K_1 + \frac{0.4\,K_2\,P}{s}\right)\right\}\right] \tag{4}$$

in which

$F_r$ = cost of building and ground
$F_a$ = cost of switchboard, wiring, protective apparatus, etc.
$f_r$ = fixed charges on building and ground as decimal
$f_e$ = fixed charges on equipment as decimal

or, putting,

$$M_1 = f_r\,F_r + f_e\,\{F_a + (1+q)\,2\,K_1\} \tag{5}$$

and

$$M_2 = f_e\,(1+q)\,0.4\,K_2\,P \tag{6}$$

$$a_s = M_1 s + M_2 \tag{7}$$

*Annual charges on overhead copper.* The overhead conductors may be proportioned according to Kelvin's law, if the losses therein can be computed without too much labor. To this end it is consistent to assume that the mean load on each sub-station is fixed at a certain distance, one-third of the length of the section, from the sub-station. Since the cross-section of the copper by Kelvin's law, for a given transmitted power, depends only on the cost of copper and the cost of the energy, the trolley can be determined for the economic condition independent of the distance that the power is transmitted from the sub-station to the car or train. However the cost of copper becomes a function of the distance between sub-stations through the fact that the losses in the overhead conductors per section vary as the car-hours per section or inversely as the number of sub-stations.

Letting

$w$ = root of mean square load per car or train in apparent watts

$v$ = trolley voltage

$h$ = car or locomotive hours per year

$s$ = number of sub-stations

$r$ = resistance per mile of trolley wire

$D = T/s$ = length of one section in miles, the end-sections being one-half the length of the others.

$T$ = total length of line in miles

$k$ = cost of one kilowatt-hour at high-tension side of sub-station in dollars

$\varepsilon$ = per cent. all-day efficiency of sub-stations

$F_c$ = cost of copper in cents per pound

$f_c$ = annual charges on copper as decimal

the following expression of Kelvin's law results:

$$\frac{w^2\, h\, D\, k\, r}{v^2\, 1000 \times 3\, s\, \varepsilon} = \frac{876\, D\, F_c\, f_c}{r\, 100} \tag{8}$$

the first member representing the annual cost of the energy lost section, and the second member the annual charges on the investment.

Solving for $r$, to obtain the cross-section of copper,

$$r = \frac{162\ v}{w} \times \sqrt{\frac{F_c\, f_c\, s\, \varepsilon}{h\, k}} \tag{9}$$

Substituting in the preceding equation the value for $r$, we obtain the total annual charges on the overhead conductors,

$$a_c = \frac{8.76 \times D\, F_c\, f_c\, s}{\dfrac{162\ v}{w} \times \sqrt{\dfrac{F_c\, f_c\, h\, k}{s\, \varepsilon}}} \tag{10}$$

or

$$a_c = \frac{0.0541\ T\ w}{v} \times \sqrt{\frac{F_c\ f_c\ h\ k}{s\ \varepsilon}} \tag{11}$$

or, placing

$$M_s = \frac{0.0541\ T\ w}{v} \times \sqrt{\frac{F_c\ f_c\ h \cdot k}{\varepsilon}} \tag{12}$$

$$a_c = \frac{M_s}{\sqrt{s}} \tag{13}$$

*Annual cost of sub-station losses.* Reverting again to the premises of the practical uniformity of line loading and the equal distribution of the total sub-station capacity along the line, it is apparent that under the assumption that the per cent. of iron and copper losses is constant for all sizes of transformers under consideration, the transformation of the given amount of energy required at the overhead conductor will entail transformer losses that will be constant and independent of the capacity or number of the individual sub-stations.

As a corollary to this conclusion, the sub-station all-day efficiency will be the same irrespective of the spacing of the stations. The error accruing from the assumption of constant transformer losses is almost negligible, and, furthermore, the omission of the cost of sub-station losses simplifies the algebraic operations in the determination of the condition for the minimum annual charges.

*Annual cost of secondary conductor losses.* The annual cost of the losses occurring in the overhead copper was computed from the expression of Kelvin's law. The secondary conductor losses should contain, to be rigorously exact, the losses occurring in the track-return, but the calculations show that these amount to only a small per cent. of the total yearly cost. This is readily seen from a comparison of the trolley and track resistances. To take the most unfavorable combination likely to occur in practice, assume an overhead wire of No. 0000 and 60-lb. rails. The ratio of track resistance to trolley resistance is 0.0422 : 0.259, or 0.163. To take the most favorable combination, No. 00 wire and 100-lb. rails, the ratio is 0.0253 : 0.412, or 0.0615. So that the track losses lie between about 6% and 16% of the copper losses.

The track losses will take a form similar to the first member of equation (8), all the factors entering being constants except the car-hours per section, and, as will appear farther on, the retention of a term with $s$ in the denominator will render the expression $d\,a/d\,s$ an equation of the third degree. The resulting value of $s$, after the algebraic solution, would be rather cumbersome to evaluate from the numerical constants, and the sacrifice of mathematical precision will not materially vitiate the practical result.

*Solution.* With the algebraic expressions for the several items constituting the total annual charges on the sub-station and overhead copper investments, we may proceed with the solution. The total annual charges,

$$a = a_s + a_c + a_c \tag{14}$$

since the annual charges on the copper are equal to the annual cost of the losses.

$$a = s\left[f_r F_r + f_e\left\{F_a + (1+q)\left(2\,K_1 + \frac{0.4\,K_2 P}{s}\right)\right\}\right] + 2\left[\frac{0.0541\,T\,w}{v} \times \sqrt{\frac{F_r\,f_c\,h\,k}{s\,\varepsilon}}\right] \tag{15}$$

Or, using the corresponding expressions,

$$a = M_1\,s + M_2 + 2\,\frac{M_3}{\sqrt{s}} \tag{16}$$

From this equation it is seen that the curve of the total annual charges is the result of a curve superposed on a straight line. Differentiating,

$$\frac{da}{ds} = M_1 - M_3\,s^{-\frac{3}{2}} \tag{17}$$

Placing the differential equal to zero and solving for $s$

$$s^{\frac{3}{2}} = \frac{M_3}{M_1} \tag{18}$$

or

$$\log s = 0.667\,(\log M_3 - \log M_1) \tag{19}$$

Hence

$$\log D - \log T/s = \log T - 0.667\,(\log M_3 - \log M_1) \tag{20}$$

It will be seen on inspection that $\frac{d^2 a}{d s^2}$ will be greater than zero, so that the value of $s$ given in equation (19) will render $a$ a minimum.

The equation $\frac{d a}{d s}$ when multiplied through by $s$, shows that *for a minimum value of the annual charges, the cost of copper is equal to that part of the cost of the sub-stations which is independent of the output.*

*Example:* To illustrate the use of this equation, there is submitted herewith a certain interurban railway project. The line is single-tracked, 110 miles in length laid with 80-lb. rails. The traffic is a mixed passenger and freight, the former being handled by 40-ton motor cars, and the latter by 60-ton locomotives. The preliminary study of the calculated run-sheets shows the following:

| Service | No. | Weight tons | Schedule speed m.p.h. | Train hours per day | Average kilowatt input |
|---|---|---|---|---|---|
| Through freight | 2 | 960 | 15 | 14.6 | 275 |
| Local freight | 4 | 480 | 21 | 21.0 | 221 |
| Express passenger | 8 | 40 | 40 | 22.0 | 104 |
| Local passenger | 16 | 40 | 32 | 55.0 | 97 |
| Baggage | 4 | 50 | 34 | 12.9 | 120 |

Total train-hours per day, 126.
Average apparent kilowatt input per train, 176.

The energy is transmitted from a power company's plant at 66,000 volts, and is transformed to 3300 volts at the sub-stations, where it is sold to the railway company at the rate of one cent per kilowatt-hour.

The cost of each sub-station building and ground was estimated uniformly at $2000, the cost of the switchboard, wiring, and protective apparatus at $1800 per sub-station, the price of copper at 15 cents per pound, and the fixed charges on these three items at 7 per cent., 15 per cent., and 8 per cent., respectively. The cost of oil-insulated self-cooling transformers in sizes of 150 kw. to 500 kw. for 25 cycles 60,000 to 3,300 volts was found to be

$$F_t^1 = 1080 + 2.9\, K\, W'$$

Hence the following numerical values result:

$$
\begin{aligned}
f_r &= 0.07\\
F_r &= 2000\\
f_a &= 0.15\\
F_a &= 1800\\
K_1 &= 1080\\
T &= 110\\
w &= 176{,}000\\
v &= 3300\\
F_c &= 15\\
f_c &= 0.08\\
h &= 46000\\
k &= 0.01\\
\varepsilon &= 0.96
\end{aligned}
$$

Then, assuming that there will be no spare transformers,

$$M_1 = 140+594 = 734$$

$$M_2 = \frac{0.0541\times 110\times 176000}{3300}\times\sqrt{\frac{15\times 0.08\times 46000\times 0.01}{0.96}}$$

$$
\begin{aligned}
M_2 &= 317\times 24.0 = 7608\\
\log M_2 &= 3.8813\\
\log M_1 &= \frac{2.8657}{1.0156}\\
\log s &= 0.6771\\
s &= 4.754
\end{aligned}
$$

which indicates that the economic condition would be about 5 sub-stations about 22 miles apart.

The required trolley section has a resistance,

$$r = \frac{162\times 3300}{176000}\times\sqrt{\frac{15\times 0.08\times 5\times 0.96}{46000\times 0.01}}$$

$$
\begin{aligned}
r &= 3.04\times 0.1118 = 0.34 \text{ ohms per mile}\\
r' &= 0.0643 \text{ ohm per 1000 ft.}
\end{aligned}
$$

which corresponds to a No. 000 wire.

Having established the number of sub-stations and the cross-section of the overhead conductor, it remains to be seen whether the consequent drop between the sub-station and the train is prohibitive. The graphic time-table shows that the maximum number of trains on the line simultaneously is as follows: one through freight, two local freights, eight passenger cars, and two baggage cars. With these trains in the most unfavorable position likely to occur, the total peak load is about 3700 kw. and the maximum input required between sub-stations is 1020 apparent kilowatts.

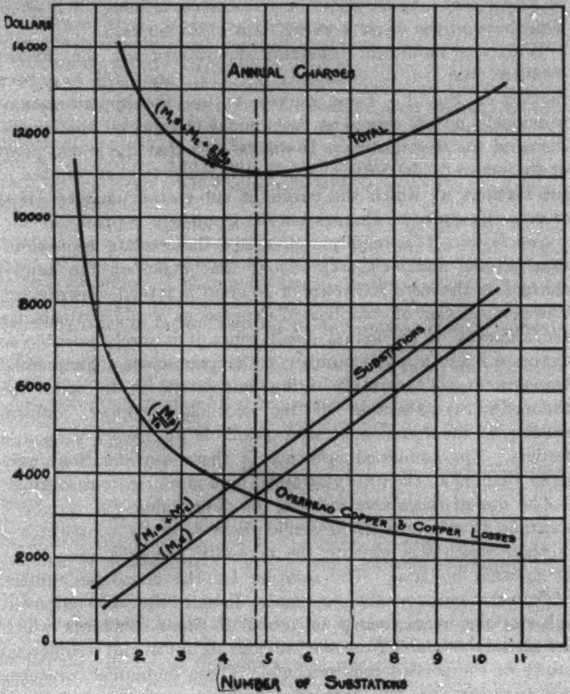

FIG. 1

Assuming that this load is at the maximum distance from the sub-station, a single catenary construction and 80-lb. rails with a total drop (ohmic and inductive) of 11.7 volts per 100 amperes per 1000 ft. will give a momentary voltage-drop of

$$\frac{1020000 \times 11.7 \times 5.28 \times 22}{2 \times 3300 \times 100 \times 2} = 1050 \text{ volts}$$

or 32 per cent., which would be permissible, although it is somewhat beyond the usual working limit of 25 per cent.

With the numerical constants determined for the present problem, the loci of equations (7), (13), and (16) have been plotted in Fig. 1. These curves, within the approximations previously noted, represent the annual charges on the several items of the distribution. It will be seen that the lowest point of the curve of the total charge corresponds to that number of sub-stations at which the curve of sub-station charges ($M_1 s$) crosses the curve of charges on the secondary copper.

*Conclusion.* It is readily appreciated that certain approximations in the analytical expressions that make up the annual charges on the installation are of no great practical consequence. The introduction of complicated expressions would not enhance the accuracy of the actual result, since it is rarely possible to evaluate $s$ into a whole number, to happen across a commercial transformer of the exact rating calculated, or to make the theoretical cross-section of the secondary copper conform exactly to the commercial sizes available for trolley wires and feeders. The combined influence of these considerations may more than offset the nicety attained by a more rigorous solution.

The use of the above formula for determining the economic location of sub-stations in single-phase railways constitutes a method which will obviate the necessity generally incumbent of solution by trial. The solution for the economic number of sub-stations, or the economic distance between adjacent sub-stations, is expressed in terms of those constants which are already available from the previous technical and commercial study of the service requirements. These numerical constants are evaluated for the particular problem at hand, and hence establish, within the scope of electric railroading problems defined at the beginning of this paper, the generality of the formula deduced.

## DISCUSSION ON "THE DETERMINATION OF THE ECONOMIC LOCATION OF SUB-STATIONS IN ELECTRIC RAILWAYS." AT ATLANTIC CITY, N. J., JULY 1, 1908.

**C. J. Hopkins:** On December 15, 1905, a paper was read before this Institute on the most economical location of sub-stations for direct-current systems.* Mr. Werner's paper only differs from that, as far as I understand it, in its particular reference to single-phase systems.

Of course, we are all familiar with the form of curves given in Fig. 1. I would not criticise the accuracy of the formulas presented by Mr. Werner, but I question their general usefulness. As simple as it may sound, it appears to me that the most important feature in working out an electrification proposition is the proper consideration and formation of a train diagram, to represent what the service will be when the electrification is completed.

In the last paragraph Mr. Werner refers to the use of his formulas as obviating the necessity of solution by trial. This seems to imply that there might be a large number of solutions by trial necessary if that were the method resorted to, but in general there are only two or three practical solutions, and as a rule, they have to be worked out in detail and carefully considered.

The specific purpose of this paper is to develop an equation for the number of sub-stations, but I do not believe that such a determination is simplified by resorting to any formula of a general nature, but rather is the result of practical consideration and sound judgment.

**Gerard B. Werner:** The paper to which Mr. Hopkins refers was typical of the method of solution by trial, by evaluating the annual charges for a different number of sub-stations. Now the adjustment of the cost of sub-stations and the cost of copper, considered as an economical problem, is quite definite, and my paper is an attempt to develop some formula to obviate the trial method.

The economic condition of the secondary distribution, whether it can be executed in the actual layout of the road or not, should be determined as a basis of reference. This consideration is the primary intent of the paper, and not the substitution of a formula for judgment, for the handling of engineering problems of this character.

To the best of my recollection, Mr. Lincoln made a contribution to the proceedings of the International Electrical Congress in St. Louis in 1904 on a similar subject, and I have no doubt that he has some comment to make on this topic.

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* "Some Considerations Determining the Location of Electric Railway Sub-Stations," by C. W. Ricker, *Transactions* A. I. E. E., Vol. XXIV p. 1097

**P. M. Lincoln:** I have not much to add to the discussion, although I have given this matter considerable thought. I am rather inclined to agree with Mr. Hopkins in his suggestion, that after having worked over this matter with a whole lot of formulas, the actual locating of sub-stations is not so much a matter of manipulation by formulas as it is a matter of judgment. It is safe to use the location obtained by formulas only when no other location is dictated by common sense.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 1, 1908.*

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# CONDUCTOR RAIL MEASUREMENTS

## BY S. B. FORTENBAUGH

*General.* The Underground Electric Railways Company of London, Ltd., control and operate electrically the Metropolitan District Railway and contingent lines, 56 miles of main-line double track, and three deep level " tube " railways, with connections, aggregating approximately 28 miles of double track. A detailed description of the electrification of the system, by the writer, appeared in the *Street Railway Journal* of March 4, 1905.

This company installed a " third " and " fourth " conductor rail on all of the above lines, both the conductor rails being of low carbon steel and supported on brown stoneware insulators. The insulators used in supporting the positive (outside) and negative (center) conductor rails are essentially of the same design on the individual roads, the top of the positive insulator being 1.5 in. higher than the negative. A malleable-iron cap and base is used on the District Railway insulators, the difference in height of the positive and negative insulator being partly in the depth of the insulation and partly in the design of the base.

No base or cap is used with any of the insulators on the Tube railways. The top of the positive conductor rail is 10 in. and 10.5 in. above the top of the sleepers on the District and tube railways respectively. Figs. 1 to 5 inclusive show the type of insulators, conductor rails, spacing, etc., as installed on the district and tube railways.

The direct-current track-circuit signal system has been installed on these roads and hence the desirability of not using the running rails as part of the main power circuit.

### LEAKAGE AND INSULATION MEASUREMENTS

*Metropolitan District Railway.* An extended series of preliminary measurements and tests were made on the Hounslow and Putney section of the District Railway early in 1905 with a view of trying to account for the comparatively low insulation resistance of the negative conductor rail. These tests were made during the constructional period; that is, before the introduction of commercial electric trains but with the regular steam trains in daily commercial service, and the insulation of the conductor rails was therefore more or less of a variable quantity and subject to the temporary changes and conditions incidental to such work.

The positive (outside) conductor rail, particularly at the stations, was heavily coated with grease from the steam trains and this, together with loose ballast, dirt, etc., made it very difficult and virtually impossible to maintain good insulation during these tests.

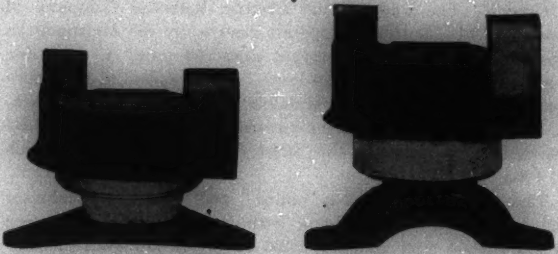


FIG 1 FIG. 2

Positive and negative insulators—District Railway

The results of these preliminary measurements were very erratic, for the reasons just given, and are therefore not included in this paper. They plainly indicated, however, the existence of the peculiar phenomena observed on the tube railways where the conditions were much more favorable for the perfectly definite and consistent observations given herewith.

The observations given in Table 1 were made in January, 1906, and show the variation in potential between conductor rails and earth from day to day. These measurements were made on the main line of the District Railway at Earls Court, the electric trains having been in commercial service since July 1, 1905.

All sections of the road are tied together and cross-bonded through the sub-station bus-bars under normal operating conditions, and these results are therefore representative of the conditions existing over the entire District Railway system, collectively considered. The continuously bonded running rail was used as the earth connection for these measurements.

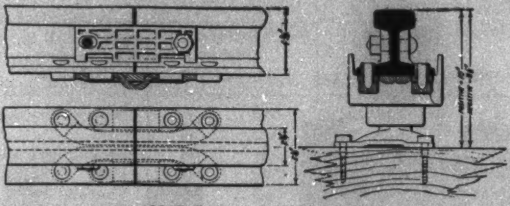
TABLE I.—LINE VOLTAGE 580

| Date—1906 | Time | Volts between earth and | | Remarks |
|---|---|---|---|---|
| | | Positive | Negative | |
| Jan. 8 | 2.15 p.m. | 530 | 50 | Ground very damp. |
| " 8 | 4.35 " | 512 | 68 | " " " |
| " 9 | 4.50 " | 500 | 80 | Ground very wet. |
| " 10 | 10.00 a.m. | 529 | 51 | Fine. |
| " 10 | 5.30 p.m. | 512 | 68 | Fine and dry. |
| " 12 | 11.00 a.m. | 510 | 70 | Fine, ground damp. |
| " 12 | 5.50 p.m. | 512 | 68 | " " " |
| " 13 | 11.00 a.m. | 490 | 90 | Ground very wet. |
| " 15 | 12.30 p.m. | 540 | 40 | Very fine. |
| " 15 | 6.00 " | 520 | 60 | Very fine and dry. |
| " 16 | 5.00 " | 512 | 68 | Showery. |
| " 18 | 12.45 " | 478 | 102 | Very wet. |
| " 22 | 5.00 " | 520 | 60 | Fine. |
| " 23 | 6.00 " | 532 | 48 | Fine, frosty. |

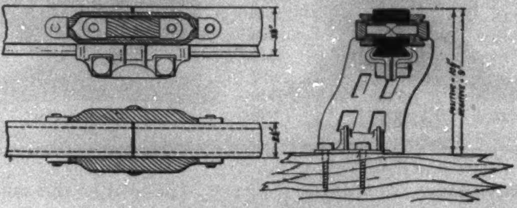
*Baker Street and Waterloo Railway.* The tests on this railway like those on the District Railway, were made about the end of the constructional period and were therefore subject, but in a much lesser degree, to the possibility of the same general disturbances.

The insulators were of brown stoneware with a good glaze, free from grease, and reasonably clean, with the exception of the usual dust from the small granite ballast and construction work. A rectangular section of conductor rail is used on this line, there being no intervening metal cap or support between the rails and insulators. These measurements were not subject to the usual outdoor variation of London weather and temperature, the section of track on which the measurements were made being entirely below the surface and far enough removed from the tunnel entrance so as to be, at the most, only possibly indirectly affected:

*Up-road, January* 2 *to* 4, 1906. The following measurements were made on the "up-road," between the cable passageway beneath the London Road sub-station and the far end of Baker street station platform, a distance of 18,317 ft. or 3.47 miles. All measurements were made from the London Road sub-station.



100 LB RAIL — DISTRICT RAILWAY



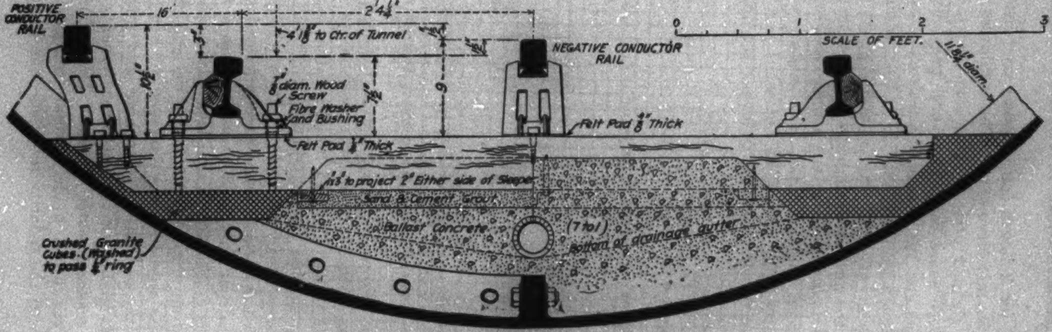
85 LB RAIL — TUBE RAILWAYS

FIG. 3—Bonding and supports for conductor rails

*Polarity of conductor rails, normal.*

| | |
|---|---|
| Between positive (outer) and negative.......... | 570 volts |
| " " and earth.............. | 510 " |
| " negative and earth................ | 60 " |
| Leakage, positive to negative.................. | 0.5 amperes |
| Leakage current per mile of single track.......... | 0.144 " |
| Leakage, positive earthed.................. | 5.0 " |
| " negative earthed.................. | 0.57 " |

Current was on from 2 to 5.30 p.m. on January 1, and from 7 to 10 a.m. January 2; that is, 2.5 hours on the preceding



POSITIVE CONDUCTOR RAIL
16'
2'4¼"
4'1⅛" to Ctr. of Tunnel
NEGATIVE CONDUCTOR RAIL
0
1
2
3
SCALE OF FEET.
11'8¼" diam.
10½"
⅞" diam. Wood Screw
Fibre Washer and Bushing
7½"
6
Felt Pad ⅛" Thick
Felt Pad ⅛" Thick
¼" to project 2" Either side of Sleeper
Sand & Cement Grout
Ballast Concrete
(7 to 1)
Bottom of drainage gutter
Crushed Granite Cubes. (Washed) to pass ⅛" ring

Fig. 4—Section illustrating type of construction, Tube Railways

afternoon and for 3 hours continuously and immediately preceding the above measurements. The insulators were supposed to have been cleaned prior to above measurements. Current had also been on these rails on several previous occasions for testing purposes and the running of trains.

*Polarity of conductor rails, reversed.* The polarity of the conductor rails was reversed immediately after the preceding readings and the pressure applied continuously for 48 hours, all other conditions remaining the same. Readings were taken regularly between the outer rail (now negative polarity) and earth, the results being shown on Fig. 6.

At the end of the 48 hours the following readings were taken:

| | |
|---|---|
| Between positive (centre) and negative | 570 volts |
| " " and earth | 455 " |
| " negative and earth | 115 " |
| Leakage, positive to negative | 0.5 amperes |
| Leakage current per mile of single track | 0.144 " |
| Leakage, positive earthed | 2.8 " |
| " negative earthed | 0.7 " |

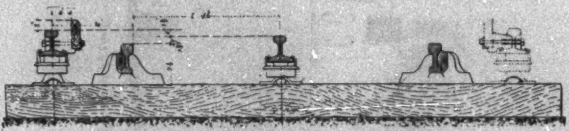


Fig. 5—Cross-section of single track, District Railway

These results show that the potential between the outer rail and earth was reduced from 510 (positive to earth) to 104 volts (negative to earth) in 24 hours. Some local disturbance then caused a sudden rise to about 118 volts, after which it again slowly but steadily fell to 115 volts at the end of 48 hours. During the first half-hour immediately following the reversal, the leakage current increased steadily from 0.5 to 1.27 amperes and then gradually became less. It reached the normal value of 0.5 of an ampere on or *before* the end of the 48 hours. The low-reading ammeter was damaged by a temporary short-circuit about the end of the first hour and was therefore not immediately available for current measurements.

*Polarity of conductor rails, normal.* The polarity of the conductor rails was again made normal—immediately after the 48-hour run with the polarity reversed—the increase in leakage

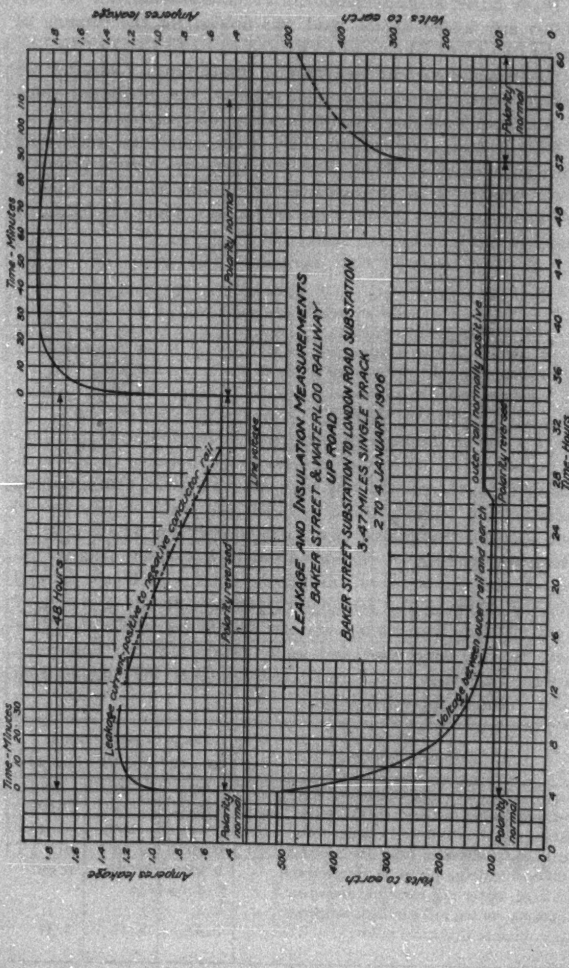

LEAKAGE AND INSULATION MEASUREMENTS
BAKER STREET & WATERLOO RAILWAY
UP ROAD
BAKER STREET SUBSTATION TO LONDON ROAD SUBSTATION
3.47 MILES SINGLE TRACK
2 TO 4 JANUARY 1906
Amperes leakage
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
Volts to earth
500
400
300
200
100
0
Time - Minutes
0 10 20 30
0 10 20 30 40 50 60 70 80 90 100 110
48 Hours
Leakage current positive to negative conductor rail
Polarity normal
Polarity reversed
Polarity normal
Line voltage
Voltage between outer rail and earth
outer rail normally positive
Polarity normal
Polarity reversed
Polarity normal
Time - Hours
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60

Fig. 6

current and the variation in potential between the outer rail and earth for the first two hours being also shown in Fig. 6.

These latter measurements unfortunately could not be continued any longer as the road was needed for the running of trains.

The leakage current rose rapidly immediately following the change from reversed to normal polarity, the maximum value of 1.92 amperes being reached in about 35 minutes.

*"Up" road, January* 16, 1906. The conductor rails were alive an average of about nine hours per day, normal polarity, from January 4 to 16 inclusive for running trains a total of 117 hours between the readings on January 4 and the following readings on January 16, 1906.

*Polarity of conductor rails, normal.*

| | |
|---|---|
| Between positive (outer) and negative | 565 volts |
| " " and earth | 530 " |
| " negative and earth | 35 " |
| Leakage, positive to negative | 0.32 amperes |
| Leakage current per mile of single track | 0.092 " |
| Leakage, positive earthed | 5.70 " |
| " negative earthed | 0.35 " |

*"Up" road, January* 19 *to* 22, 1906. The following measurements show the effects of reversing the polarity of the conductor rails, the rails having been alive about 24 hours, normal polarity, for running trains between the tests of January 16 and 19. The rails were alive continuously for 43.5 hours between the readings of January 19 and 21 with the polarity reversed; that is, outer rail negative—and for 21 hours, normal polarity, between the readings of January 21 and 22. Fig. 7 gives full details of these tests and Fig. 6 the details of similar tests on the same road and under practically the same conditions. All the "Up" road measurements were made from the London Road sub-station.

| General exhibit | Date of tests—1906 | | |
|---|---|---|---|
| | Jan. 19 | Jan. 21 | Jan. 22 |
| Between positive and negative, volts | 575 | 575 | 575 |
| Between outer rail and earth, volts | 531 | 112 | 530 |
| Between centre rail and earth, volts | 44 | 463 | 45 |
| Leakage, positive to negative, amperes | 0.29 | 0.35 | 0.3 |
| Amperes leakage per mile single track | 0.084 | 0.101 | 0.087 |
| Leakage, outer rail earthed, amperes | 4.3 | | |
| Leakage, centre rail earthed, amperes | 0.3 | | |
| Approximate distance, miles | 3.47 | 3.47 | 3.47 |

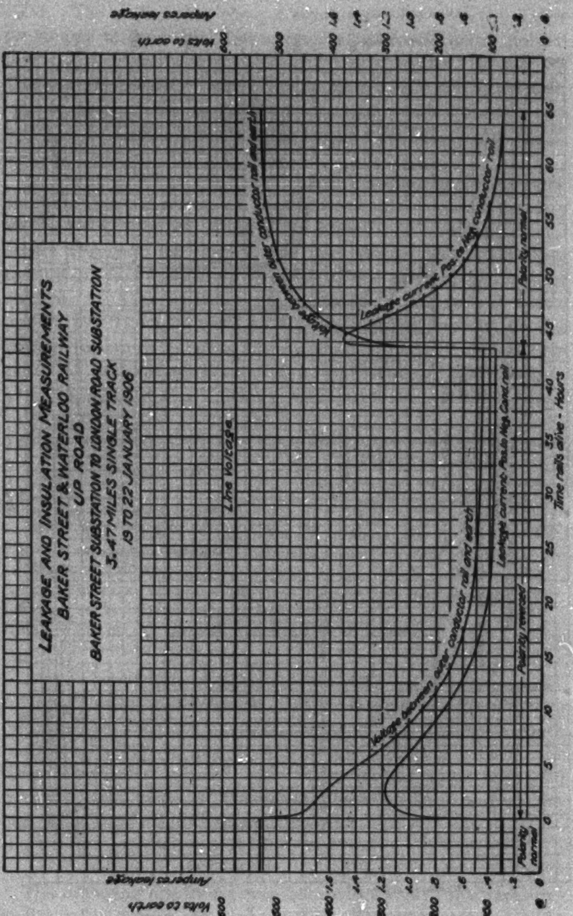

LEAKAGE AND INSULATION MEASUREMENTS
BAKER STREET & WATERLOO RAILWAY
UP ROAD
BAKER STREET SUBSTATION TO LONDON ROAD SUBSTATION
3.47 MILES SINGLE TRACK
19 TO 22 JANUARY 1906
Line Voltage
Voltage between outer conductor rail and earth
Leakage current Pos. to Neg. Cond. rail
Voltage between outer conductor rail and earth
Leakage current Pos. to Neg. conductor rail
Polarity normal
Polarity reversed
Polarity normal
Volts to earth
Amperes leakage
600
500
400 1.6
1.4
300 1.2
1.0
200 .8
.6
100 .4
.2
0 0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time rails alive - Hours

FIG. 7

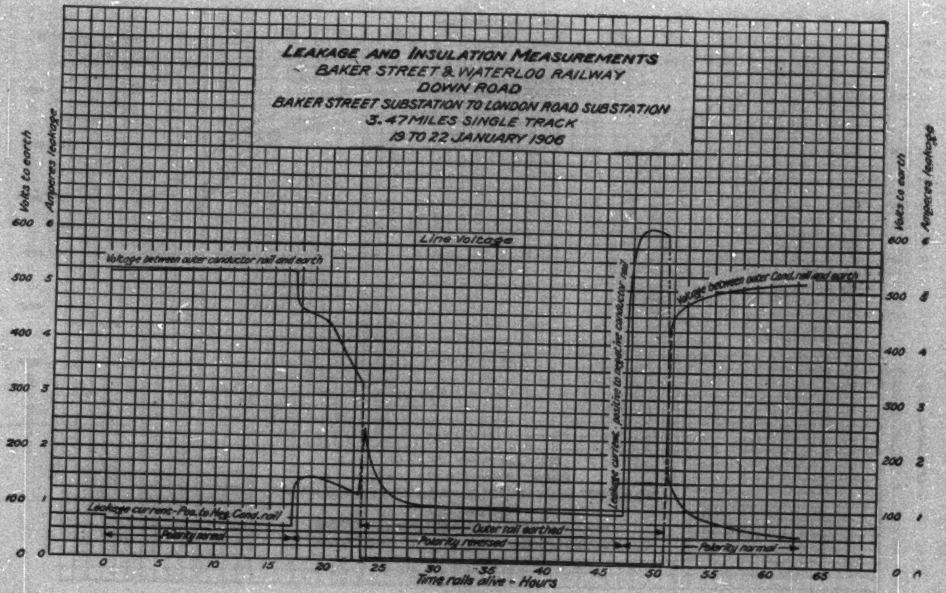

LEAKAGE AND INSULATION MEASUREMENTS
BAKER STREET & WATERLOO RAILWAY
DOWN ROAD
BAKER STREET SUBSTATION TO LONDON ROAD SUBSTATION
3.47 MILES SINGLE TRACK
19 TO 22 JANUARY 1906
Volts to earth
Amperes leakage
600 6
500 5
400 4
300 3
200 2
100 1
0 0
Line Voltage
Voltage between outer conductor rail and earth
Leakage current - Pos. to Neg. Cond. rail
Polarity normal
Outer rail earthed
Polarity reversed
Leakage current - positive to negative conductor rail
Voltage between outer Cond. rail and earth
Polarity normal
0 5 10 15 20 25 30 35 40 45 50 55 60 65
Time rails alive - Hours

FIG. 8

*"Down" road, January* 19 *to* 22 *and February* 12, 1906. The initial measurements for this road were made on January 19, 1906. The rails were alive continuously for about 8 hours previously to the initial measurements and for 17 hours, normal polarity, between the measurements on January 19 and 20. The normal polarity was reversed immediately after the readings on January 20 for 30 hours and again made normal for 15 hours, a total of 45 hours between the readings of January 20 and 22.

A temporary but effective "earth" mysteriously appeared on the outer rail about six hours after the reversal on January 20, this condition of affairs being maintained continuously for about 28 hours, four hours after the polarity was again made normal on January 21. The effect of this earth on the leakage current, together with the other details of this test, is shown in Fig. 8. The rails were alive daily, normal polarity, for the running of trains between the readings of January 22 and February 12, a total of about 260 hours between these readings. The readings for the "down" road, made at the Baker Street sub-station, are as follows:

| General Exhibit | Date of tests—1906 | | | |
|---|---|---|---|---|
| | Jan. 19 | Jan. 20 | Jan. 22 | Feb. 12 |
| Between positive and negative, volts.. | 575 | 575 | 575 | 575 |
| Between outer rail and earth, volts... | 520 | 525 | 515 | 499 |
| Between centre rail and earth, volts... | 55 | 50 | 60 | 76 |
| Leakage, positive to negative, amperes | 0.68 | 0.58 | 0.55 | 0.2 |
| Amperes leakage per mile single track. | 0.196 | 0.167 | 0.158 | 0.058 |
| Leakage, outer rail earthed, amperes.. | 6.75 | | | 3.0 |
| Leakage, centre rail earthed, amperes. | 0.74 | 0.62 | | 0.25 |
| Approximate distance, miles.......... | 3.47 | 3.47 | 3.47 | 3.47 |

The following observations, Table II, show the variations in potential between the positive conductor rail and earth—both roads—from day to day as well as the variation between the time of switching "on" and "off" on the same day. All measurements made by the sub-station attendants at the London Road sub-station, normal polarity.

## Discussion of Results

The following results are corroborated by many other measurements made during the years of 1903-1907, all of which plainly and unmistakably show the existence of the phenomena substantially as illustrated in Figs. 6, 7 and 8. There has been considerable study and investigation as to what actually takes place at the time of reversal, the general concensus of opinion being that it is an ordinary case of electrolytic action combined with ordinary insulation resistance conductivity. These results seem to depend upon one form of phenomenon which has long been known in connection with static charges; namely, that a negatively charged conductor leaks away its charge with much greater facility than does a positive; or virtually that under the same conditions a positively electrified conductor is better insulated. A negatively electrified conductor appears to be continuously

TABLE II.—LINE VOLTAGE 575

| Date—1906 | Time | Hours rails alive to-day | Volts between positive and earth | |
|---|---|---|---|---|
| | | | Up-road | Down-road |
| Jan. 24 | 7.00 p.m. | 19 | 525 | 512 |
| " 25 | 10.30 a.m. | | 500 | 510 |
| " 25 | 8.00 p.m. | 9.5 | 540 | 512 |
| " 26 | 10.00 a.m. | | 500 | 495 |
| " 26 | 7.30 p.m. | 9.5 | 540 | 506 |
| " 27 | 10.00 a.m. | | 510 | 445 |
| " 27 | 3.30 p.m. | 5.5 | 535 | 503 |
| " 29 | 10.00 a.m. | | 465 | 410 |
| " 29 | 7.00 p.m. | 9.0 | 560 | 575 |
| " 30 | 10.00 a.m. | | 530 | 452 |
| " 30 | 8.30 p.m. | 10.5 | 565 | 510 |
| " 31 | 8.00 a.m. | | 522 | 462 |
| " 31 | 8.30 p.m. | 12.5 | 530 | 480 |
| Feb. 1 | 9.00 a.m. | | 490 | 430 |
| " 1 | 7.30 p.m. | 10.5 | 540 | 495 |
| " 2 | 8.30 a.m. | | 498 | 452 |
| " 2 | 7.30 p.m. | 11.0 | 500 | 465 |
| " 3 | 8.00 a.m. | | 484 | 444 |
| " 3 | 4.30 p.m. | 8.5 | | |
| " 4 | 9.00 a.m. | 15 | 463 | 440 |
| " 5 | 8.00 p.m. | 20 | 493 | 469 |
| " 7 | 9.00 a.m. | | 505 | 480 |
| " 7 | 9.00 p.m. | 12 | 505 | 495 |
| " 9 | 9.30 a.m. | 14.5 | 486 | 444 |
| " 10 | 5.30 p.m. | 17.5 | 520 | 492 |

discharging negative ions, which have the effect of conferring conductivity on the surrounding gas and of causing deposition of moisture from air more or less saturated. It is perfectly conceivable, therefore, that this negative discharge should favor the depositing of moisture between the surfaces of insulators progressively in such a manner that a slight conductivity might be conferred upon the insulator surfaces and that this effect might be expected to be absent with the positive side of the system. The film of liquid existing between the electrodes on a glass surface will gradually move from the positive to the negative electrode, and the negative insulators may therefore lose their insulating properties by having moisture drawn upon them, an action which does not take place on the positive side.

The reducing or chemical action of the ions liberated at the positive rail insulator may result in the formation of compounds which lower the resistance of the negative insulator, while the oxidation which takes place at the positive insulator may improve the insulation.

*Conclusions*. These results, whatever the immediate cause or the reason, have clearly demonstrated certain facts which are probably applicable to all similar installations and may be briefly summarized as follows:

1. That the difference of potential between the positive conductor and earth is always normally considerably greater than the potential existing between the negative conductor and earth.
2. That this difference between the positive and negative insulation becomes more marked the longer the conductors are subjected continuously to a difference of potential in the same direction.
3. That a reversal of the polarity is always instantly accompanied by a considerable increase in the normal leakage current between the positive and negative conductor.
4. The above phenomena can be repeated indefinitely and are independent of the length of time that the pressure has been previously applied to the conductors in either direction.
5. That the insulation of the negative conductor to earth can not be proportionately maintained.

*Resistance of conductor rails*. The resistance measurements given in Table III show about what may be expected commercially with a soft conductor rail containing an unusually small amount of manganese and carbon. The resistance of these rails was about 6.4 times that of an equivalent area of copper and the chemical composition substantially as follows:

| | |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.19 |
| Sulphur | 0.06 |
| Phosphorus | 0.05 |
| Silicon | 0.03 |

It is interesting to note that the cost of this special conductor rail was no more than the standard track rail.

TABLE III.—RESISTANCE MEASUREMENTS

| General exhibit | Section of railway | | | |
|---|---|---|---|---|
| | Hounslow | Putney | Wimbledon | B. St. & W. |
| *General Data:* | | | | |
| Date of measurements | 5/9/05 | 5/27/05 | 5/27/05 | 12/30/05 |
| Net length measured, feet | 88,300 | 37,700 | 53,500 | 36,600 |
| Weight of rail per yd., lb. | 100 | 100 | 100 | 85 |
| Area of rail, sq. in. | 9.86 | 9.86 | 9.86 | 8.3 |
| Temp. of rails, deg. cent. | 25 | 25 | 25 | 11.5 |
| No. of switchboard contacts | 0 | 4 | 4 | 2 |
| No. of terminal post contacts | 20 | 20 | 32 | 6 |
| No. of rail contacts | 20 | 24 | 44 | 36 |
| No. of bonds per joint | 4 | 4 | 4 | 4 |
| Total no. of bonded joints | 2,107 | 834 | 1,160 | 1,095 |
| Area bonds per joint, sq. in. | 1.57 | 1.57 | 1.57 | 1.33 |
| Contact area per joint, sq. in. | 9.4 | 9.4 | 9.4 | 12.56 |
| *Measurements.* | | | | |
| A, Total resistance | 0.55309 | 0.24405 | 0.36412 | 0.24088 |
| B, Total resistance | 0.54856 | 0.22992 | 0.35013 | 0.23353 |
| A, Res. per 1000 ft. of rail—ohms | 0.006264 | 0.006473 | 0.006806 | 0.006581 |
| B, Res. per 1000 ft. of rail—ohms | 0.006213 | 0.006099 | 0.006544 | 0.006381 |
| A. Res. per mile-ohm | 0.033070 | 0.034180 | 0.035936 | 0.03475 |
| B, Res. per mile-ohm | 0.032805 | 0.032203 | 0.034552 | 0.03369 |
| A, Equiv. cu. area, sq. in. | 1.328 | 1.285 | 1.222 | 1.2 |
| B, Equiv. cu. area, sq. in. | 1.339 | 1.364 | 1.271 | 1.236 |
| A, Rel. resistance, cu. at 1. | 7.42 | 7.67 | 8.07 | 6.92 |
| B, Rel. resistance, cu. at 1. | 7.36 | 7.22 | 7.75 | 6.72 |
| B, Contact res. per jt., ohm. | 0.0000341 | 0.0000316 | 0.0000528 | 0.00001044 |
| B, Contact res. per bond terminal, ohm | 0.0000681 | 0.0000632 | 0.0001056 | 0.00002088 |

A includes the resistance of all feeder, track and jumper cables and the terminal post, rail and switchboard contact resistance; that is, the resistance of the bonded conductor rails, cables and contacts as installed and ready for commercial service.

B same as " A " less the calculated resistance of all feeder, track and jumper cables; that is, includes the resistance of the bonded conductor rails and auxiliary contacts.

*Remarks.* All calculated resistances are based on the temperature at which the measurements were made.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 2, 1908.*

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# THE GENERAL EQUATIONS OF THE ELECTRIC CIRCUIT

BY CHARLES P. STEINMETZ

*Introduction.* The following investigation of the general equations of the electric circuit was carried out during the last year, and necessarily is still very incomplete, and in some instances may require modification. As, however, our incomplete knowledge of the phenomena resulting from the stored energy of the electric field is at present the main hindrance to a practically unlimited extension of high potential transmission and distribution, the study of these phenomena represents the most important problem of electrical engineering, and the following outline is given in the hope of inducing other investigators to take up and continue the study of the subject.

As in all theoretical investigations, the most important part is the practical interpretation of the mathematical equations. Some such interpretations have been attempted throughout the following and may be read even without following the equations from which they are derived.

This paper represents an attempt to investigate mathematically the phenomena which may occur in the most general case of an electric circuit.

The general equations of the electric circuit, *i.e.*, equations which represent current and voltage in any circuit or circuit section irrespective of the character of power, voltage etc., can be derived under the condition that the constants of the electric circuit: resistance, inductance, conductance, and capacity are constant.

These equations are given by a sum of terms or groups containing trigonometrical and exponential functions of time and distance, and the differences between all the phenomena which may occur in electric circuits merely result from different numerical values of the integration constants of this general equation.

Each group or term comprises four waves of the same frequency—two propagate in the one, the other two in the opposite direction—and can be considered as comprising two component waves, each consisting of a wave and its reflected wave, or return wave.

One of the component waves increases in the direction of propagation, the other decreases. The former, however, decreases with the time more rapidly than the latter.

A standing wave is a wave in which the component waves coincide. A standing wave has the same intensity throughout the circuit. It starts at maximum value and dies out with the time at a rate corresponding to the dissipation of energy in the circuit, as given by the time constant of the circuit.

The general wave, comprising two component waves (each consisting of main wave and return wave), gradually builds up to a maximum and then dies out again. One of the component waves dies out slower, the other faster than corresponds to the energy dissipation in the circuit, and the former decreases while the latter increases with the distance.

A free oscillation of a circuit is a wave in which no energy is supplied to or abstracted from the circuit.

The free oscillation of a uniform circuit is a standing wave, but a standing wave is not necessarily a free oscillation.

The electric wave in a uniform circuit is oscillatory in time if its frequency is high and the circuit of moderate length. With very low frequency or extreme length, as in submarine cables, or long distance telephone lines, waves may occur which are not oscillatory, but logarithmic.

In overhead transmission lines and underground cable systems all phenomena which may result in excessive voltages or currents are oscillatory in nature.

In a traveling wave each component wave traverses the circuit at constant velocity and wave shape, and an amplitude which decreases with the distance traveled, but at any point rises from zero to a maximum, and then gradually decreases again to zero. It is not a free oscillation, but energy is transferred along the circuit by it.

The phenomena of alternating currents are those of a general wave in which the time decrement of the first component wave vanishes, that is, the energy transfer constant $f$ equals the time constant $w$.

In a complex circuit, that is, circuit containing a number of sections of different constants, the same general equation can be extended throughout the entire circuit and across the transition points between different sections of the circuit of different constants, by using as distance variable the velocity of propagation of the wave in each section of the circuit.

The free oscillation of a complex circuit is not a standing wave, and the equations of the standing wave do not apply to it, but is a general wave in which the intensity of the wave increases or decreases with the distance in each section, and energy transfer occurs between the different sections of the circuit.

The free oscillation of a complex circuit dies out at a rate given by the mean time decrement, or mean time constant of the entire circuit.

Those sections having an individual time constant greater than the mean time constant of the entire circuit receive energy from the adjoining sections, while those sections having an individual time constant less than the mean time constant of the entire circuit supply energy to the rest of the circuit during a free oscillation.

During a free oscillation of a complex circuit each section of the circuit does not perform a free oscillation.

In a section of high energy dissipation, as a transmission line, the oscillation may last very much longer, and be of lower frequency, if this section is a part of a complex oscillating circuit, than if the section oscillates alone.

In the free oscillation of a complex circuit the entire length of the circuit, when expressed in velocity measure, represents a complete wave, or a half wave, or a quarter wave, or a multiple thereof.

In the free oscillation of a complex circuit the energy of the electric field of each section divides between the energy dissipated in the section and the energy transferred to other sections (or received) in a proportion depending upon the circuit constants.

At a transition point between sections of a complex circuit, the general equations remain the same when expressed with the propagation velocity as distance unit, but the numerical values of the integration constants change.

At a transition point between sections of a complex circuit transformation of current and voltage, reflection and refraction occurs.

A single wave at a transition point is partly reflected, partly transmitted, but without change of phase angle, that is, the reflected and the transmitted wave have at the transition point the same phase angle as the incident wave.

A single wave at a transition point divides between transmitted and reflected wave in a proportion depending upon the circuit constants.

The greater the change of constants at the transition point, the greater is the reflected and less the transmitted wave.

In a general wave, at a transition point, a transformation of current and voltage occurs by a ratio proportional to the circuit constant $\sqrt{\frac{L}{C}}$.

When traversing a transition point a refraction occurs, so that the ratio of the tangents of the distance phase angle of the wave at the two sides of the transition point is constant and equal to the voltage transformation ratio.

## I. Derivation of General Equations

1. The energy relations of an electric circuit are characterized by the four constants:

$r$ = effective resistance, representing the power consumption depending upon the current, $i^2 r$, or the energy voltage, $i r$, consumed in the circuit.

$L$ = effective inductance, representing the energy storage depending upon the current, $\frac{i^2 L}{2}$, as electromagnetic component, $i L$, of the electric field; or the voltage induced by a change of the current, $L \frac{d i}{d t}$.

$g$ = effective shunted conductance, representing the power consumption depending upon the voltage, $e^2 g$, or the energy current, $e g$, consumed in the circuit.

$C$ = effective capacity, representing the energy storage depending upon the voltage, $\frac{e^2 C}{2}$, as electrostatic component, $e C$, of the electric field, or the current consumed by a change of the voltage, $C \frac{de}{dt}$.

As every circuit element consumes and stores energy, and so contains all four circuit constants, the assumption usually made in the investigation of electric circuits, that these four constants $r, L, g, C$, are localized, is permissible only in cases dealing with the usual phenomena of direct and of alternating currents, but fails when dealing with the transient phenomena resulting from the readjustment of the circuit to changes of circuit conditions, to external influences such as lightning, or when investigating high frequency phenomena, voltage and current distribution in long distance high potential circuits, cables, telephone lines, etc., and $r$, $L$, $g$, $C$, must then be treated as distributed throughout the circuit.

As $r$, $L$, $g$, $C$, are denoted the effective resistance, inductance, conductance, and capacity, per unit length of circuit, choosing as unit of length of the circuit whatever may be suitable, a centimeter in the high frequency oscillation over the multigap lightning-arrester circuit, or a mile in a long distance transmission circuit, or high potential cable.

In the most general case of an electric circuit or circuit section, it is possible to derive from the constants of the circuit, $r$, $L$, $g$, $C$, and without any assumption whatever regarding current, voltage, etc., general equations of the electric circuit, and some results and conclusions from such equations, which are based on the single assumption, that the constants $r$, $L$, $g$, $C$, remain constant with the time, $t$, and distance, $u$; *i.e.*, are the same for every unit length of the circuit or section of the circuit to which the equations apply. Where the circuit constants change, as where another circuit joins it, the integration constants in the equations also change correspondingly.

Special cases of these general equations then are all the phenomena of direct currents, alternating currents, discharges of reactive coils, high frequency oscillations, traveling waves, etc., and the differences between these different circuits are due merely to different values of the integration constants.

2. In a circuit, or a section of a circuit, containing distributed resistance, inductance, conductance, and capacity, as a transmission line, cable, high potential coil of transformer, telephone or telegraph circuit, etc., let:

$r$ = effective resistance, per unit length of circuit.
$L$ = effective inductance, per unit length of circuit.
$g$ = effective shunted conductance, per unit length of circuit.
$C$ = effective capacity, per unit length of circuit.

Let the time be denoted by $t$, and the distance from some starting point by $u$.

Let $e$ = voltage, and $i$ = current, at any point $u$ and at any time $t$.

$e$ and $i$ are functions of time $t$ and distance $u$.

For any element $d\,u$ of the circuit, the differential equations then apply:

$$\frac{d\,e}{d\,u} = r\,i + L\,\frac{d\,i}{d\,t} \tag{1}$$

$$\frac{d\,i}{d\,u} = g\,e + C\,\frac{d\,e}{d\,t} \tag{2}$$

Differentiating (1) after $t$, and (2) after $u$, and substituting (1) into (2), gives:

$$\frac{d^2\,i}{d\,u^2} = r\,g\,i + (r\,C + g\,L)\,\frac{d\,i}{d\,t} + L\,C\,\frac{d^2\,i}{d\,t^2} \tag{3}$$

and in the same manner:

$$\frac{d^2\,e}{d\,u^2} = r\,g\,e + (r\,C + g\,L)\,\frac{d\,e}{d\,t} + L\,C\,\frac{d^2\,e}{d\,t^2} \tag{4}$$

These differential equations, of second order, of current $i$ and voltage $e$, are identical. That is:

In an electric circuit, current and electromotive force are represented by the same equations, differing by the integration constants only, which are derived from the terminal conditions of the problem.

Equation (3) is integrated by terms of the form:

$$i = A\,\varepsilon^{-v u - s t} \tag{5}$$

Substituting (5) in (3) gives the identity:

$$\begin{aligned} v^2 &= r\,g - (r\,C + g\,L)\,s + L\,C\,s^2 \\ &= (s\,L - r)\,(s\,C - g) \end{aligned} \tag{6}$$

In the terms of the form (5), the relation (6) must exist between the coefficients of $u$ and $t$.

Substituting (6) into (1) gives:

$$\frac{de}{du} = (r - sL) A \varepsilon^{-vu-st} \tag{7}$$

and, integrated:

$$e = \frac{sL - r}{v} A \varepsilon^{-vu-st} \tag{8}$$

In their most general form, the *Equations of the Electric Circuit* are:

$$i = \sum^{n} \{A_n \varepsilon^{-v_n u - s_n t}\} \tag{9}$$

$$e = \sum^{n} \left\{\frac{s_n L - r}{v_n} A_n \varepsilon^{-v_n u - s_n t}\right\} \tag{10}$$

$$v_n^2 - (s_n L - r)(s_n C - g) = 0 \tag{11}$$

where $A_n$, $v_n$, and $s_n$, are integration constants, the latter two being related to each other by the equation (11).

3. These pairs of integration constants: $A_n$, $v_n$ and $s_n$, are determinated by the terminal conditions of the problem, as the current and voltage at fixed points of the circuit as function of time, or the distribution of current and voltage at a fixed time as function of the distance, etc.

While $i$ and $e$ must always be real quantities; $v_n$ and $s_n$ as exponents may be complex quantities, and in this case, the integration constants, $A_n$, are such complex quantities, that by combining the different exponential terms of the same index $n$, the imaginary terms in $A_n$ and $\frac{s_n L - r}{v_n} A_n$ cancel.

Denoting, in the exponential function:

$$\varepsilon^{-vu-st}$$

$$v = h + jk \tag{12}$$

$$s = p + jq$$

it i

$$\varepsilon^{-vu-st} = \varepsilon^{-hu-pt} \quad \varepsilon^{-j(ku+qt)}$$

and the latter term resolves into trigonometric functions of the angle:

$$k\,u + q\,t$$

$$k\,u + q\,t = \text{constant} \tag{13}$$

so gives the relation between $u$ and $t$ for constant phase of the oscillation or alternation of the current or voltage.

With change of time $t$, the phase changes in position $u$, in the circuit, *i.e.*, moves along the circuit, and the velocity of this motion is given by differentiating (13) after $t$ as

$$V = \frac{d\,u}{d\,t} = -\frac{q}{k} \tag{14}$$

that is:

$$V = -\frac{q}{k} \tag{15}$$

is the velocity of *propagation of the electric phenomena in the circuit.*

(If no energy losses occur, $r = 0$, $g = 0$, in a straight conductor in a medium of unit magnetic and dielectric constant, that is, unit permeability and unit inductive capacity; $V$ is the velocity of light.)

4. Since (11) is a quadratic equation, several pairs or corresponding values of $v$ and $s$ exist, which correspond to the same equation (11), and can be combined with each other into a group.

Such a group of terms, of the same index $n$ is defined by the equation (11):

$$v^2 = (s\,L - r)\,(s\,C - g) \tag{16}$$

and substituting:

$$v = v_1\sqrt{L\,C} \tag{17}$$

and also:

$$\begin{aligned} v &= h + j\,k \\ v_1 &= h_1 + j\,k_1 \\ s &= p + j\,q \end{aligned} \tag{18}$$

Hence:

$$\left.\begin{aligned} h &= h_1 \sqrt{L\,C} \\ k &= k_1 \sqrt{L\,C} \end{aligned}\right. \qquad (19)$$

it is, substituting (18) in (16):

$$(h_1 + j\,k_1)^2 = \left[(p + j\,q) - \frac{r}{L}\right] \left[(p + j\,q) - \frac{g}{C}\right] \qquad (20)$$

resolved, and substituting:

$$w = \tfrac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right) \qquad (21)$$

$$m = \tfrac{1}{2}\left(\frac{r}{L} - \frac{g}{C}\right) \qquad (22)$$

$$p = f + w \qquad (23)$$

gives:

$$\left.\begin{aligned} h_1^2 - k_1^2 &= f^2 - q^2 - m^2 \\ h_1\,k_1 &= f\,q \end{aligned}\right\} \qquad (24)$$

and:

$$\left.\begin{aligned} f^2 - q^2 &= h_1^2 - k_1^2 + m^2 \\ f\,q &= h_1\,k_1 \end{aligned}\right\} \qquad (25)$$

hence:

$$\left.\begin{aligned} h &= \sqrt{L\,C}\,\sqrt{\tfrac{1}{2}\,\{R_1^2 + f^2 - q^2 - m^2\}} \\ k &= \sqrt{L\,C}\,\sqrt{\tfrac{1}{2}\,\{R_1^2 - f^2 + q^2 + m^2\}} \\ R_1^2 &= \sqrt{(f^2 + q^2 - m^2)^2 + 4\,q^2\,m^2} = \frac{h^2 + k^2}{L\,C} \end{aligned}\right\} \qquad (26)$$

or:

$$\left.\begin{aligned} f &= \frac{1}{\sqrt{L\,C}}\sqrt{\tfrac{1}{2}\,\{R_2^2 + h^2 - k^2 + L\,C\,m^2\}} \\ q &= \frac{1}{\sqrt{L\,C}}\sqrt{\tfrac{1}{2}\,\{R_2^2 - h^2 + k^2 - L\,C\,m^2\}} \end{aligned}\right\} \qquad (27)$$

$$R_2^2 = \sqrt{(h^2+k^2+L\,C\,m^2)^2 - 4\,L\,C\,k^2\,m^2} = L\,C\,(f^2+q^2)$$

This gives eight pairs of corresponding values of $v$ and $s$:

$$\left.\begin{array}{llll}
1. & v = +h+j\,k & & s = w-f-j\,q \\
 & \quad\; +h-j\,k & & \quad\; w-f+j\,q \\
2. & v = -h-j\,k & & s = w-f-j\,q \\
 & \quad\; -h+j\,k & & \quad\; w-f+j\,q \\
3. & v = -h+j\,k & & s = w+f-j\,q \\
 & \quad\; -h-j\,k & & \quad\; w+f+j\,q \\
4 & v = +h-j\,k & & s = w+f-j\,q \\
 & \quad\; +h+j\,k & & \quad\; w+f+j\,q
\end{array}\right\} \qquad (28)$$

Substituting these values in the general equations (9) and (10), and in the usual manner transforming the exponential functions of imaginary exponents, into trigonometric functions, and substituting for the integration constants, $A$, the new constants:

$$C = A + A'$$

$$C' = j\,(A - A')$$

then gives as the general expression of the

*Equations of the Electric Circuit*:

$$\begin{aligned}
i = \Sigma[&\varepsilon^{-hu-(w-f)t}\,\{C_1 \cos(qt-ku) + C_1' \sin(qt-ku)\} && (i_1) \\
-&\varepsilon^{+hu-(w-f)t}\,\{C_2 \cos(qt+ku) + C_2' \sin(qt+ku)\} && (i_2) \\
+&\varepsilon^{+hu-(w+f)t}\,\{C_3 \cos(qt-ku) + C_3' \sin(qt-ku)\} && (i_3) \\
-&\varepsilon^{-hu-(w+f)t}\,\{C_4 \cos(qt+ku) + C_4' \sin(qt+ku)\}] && (i_4)
\end{aligned} \qquad (29)$$

$$\begin{aligned}
e = \Sigma[&\varepsilon^{-hu-(w-f)t}\,\{(c_1'\,C_1' - c_1\,C_1) \cos(qt-ku) - (c_1'\,C_1 + c_1\,C_1') \\
&\quad \sin(qt-ku)\} \qquad (e_1) \\
+&\varepsilon^{+hu-(w-f)t}\,\{(c_1'\,C_2' - c_1\,C_2) \cos(qt+ku) - (c_1'\,C_2 + c_1\,C_2') \\
&\quad \sin(qt+ku)\} \qquad (e_2) \\
+&\varepsilon^{+hu-(w+f)t}\,\{(c_2'\,C_3' - c_2\,C_3) \cos(qt-ku) - (c_2'\,C_3 + c_2\,C_3') \\
&\quad \sin(qt-ku)\} \qquad (e_3)
\end{aligned} \qquad (30)$$

$$+\varepsilon^{-hu-(m+f)t}\left\{(c_2' C_4' - c_2 C_4)\cos(qt+ku) - (c_2' C_4 + c_2 C_4')\sin(qt+ku)\right\}\Big] \qquad (e_4)$$

where $C_1$, $C_1'$, $C_2$, $C_2'$, $C_3$, $C_3'$, $C_4$, $C_4'$, and two of the four values, $f$, $q$, $h$, $k$, are integration constants, depending on the terminal conditions, and:

$$\left.\begin{aligned}
c_1 &= \frac{q\,k + h\,(m+f)}{h^2+k^2}\,L \\
c_1' &= \frac{k\,(m+f) - q\,h}{h^2+k^2}\,L \\
c_2 &= \frac{q\,k - h\,(m-f)}{h^2+k^2}\,L \\
c_2' &= \frac{k\,(m-f) + q\,h}{h^2+k^2}\,L
\end{aligned}\right\} \qquad (31)$$

and:

$$\left.\begin{aligned}
w &= \tfrac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right) \\
m &= \tfrac{1}{2}\left(\frac{r}{L} - \frac{g}{C}\right)
\end{aligned}\right\} \qquad (32)$$

and $h$, $k$, and $f$, $q$, are related by the equations:

$$\left.\begin{aligned}
h &= \sqrt{L\,C}\sqrt{\tfrac{1}{2}\{R_1^2 + f^2 - q^2 - m^2\}} \\
k &= \sqrt{L\,C}\sqrt{\tfrac{1}{2}\{R_1^2 - f^2 + q^2 + m^2\}} \\
R_1^2 &= \sqrt{(f^2 + q^2 - m^2)^2 + 4\,q^2\,m^2}
\end{aligned}\right\} \qquad (33)$$

hence:

$$h^2 + k^2 = L\,C\,R_1^2 \qquad (34)$$

or:

$$\left.\begin{aligned}
f &= \frac{1}{\sqrt{LC}}\sqrt{\tfrac{1}{2}\{R_2^2 + h^2 - k^2 + L\,C\,m^2\}} \\
q &= \frac{1}{\sqrt{LC}}\sqrt{\tfrac{1}{2}\{R_2^2 - h^2 + k^2 - L\,C\,m^2\}} \\
R_2^2 &= \sqrt{(h^2 + k^2 + L\,C\,m^2)^2 - 4\,L\,C\,k^2\,m^2}
\end{aligned}\right\} \qquad (35)$$

hence

$$f^2+q^2=\frac{R_2^2}{L\,C} \tag{36}$$

## II. DISCUSSION OF GENERAL EQUATIONS.

5. The general equations of current and voltage of a circuit or section of circuit having uniformly distributed and constant values of $r$, $L$, $g$, $C$, appear as a sum of groups of four terms each, characterized by the feature, that the four terms of each group have the same values of $f$, $q$, $h$, $k$.

Of the four terms of each group, $i_1$, $i_2$, $i_3$ $i_4$, or $e_1$, $e_2$, $e_3$, $e_4$, respectively (equations (29) and (30)), two contain the angles $(qt-ku)$: $i_1$, $e_1$, and $i_3$, $e_3$; and two contain the angles $(qt+ku)$: $i_2$, $e_2$, and $i_4$, $e_4$.

In the former, the velocity of propagation is:

$$\frac{d\,u}{d\,t}=+\frac{q}{k}$$

hence positive, that is, towards raising $u$.

In the latter, the velocity of propagation is:

$$\frac{d\,u}{d\,t}=-\frac{q}{k}$$

or negative, that is, towards decreasing $u$.

Each group consists of two waves and their reflected waves.

$i'=i_1-i_2$ and $e'=e_1+e_2$ is the first wave and its reflected wave, and

$i''=i_3-i_4$ and $e''=e_3+e_4$ is the second wave and its reflected wave.

In the first wave, $i'$, $e'$, the amplitude decreases in the direction of propagation, $\varepsilon^{-hu}$ for rising, $\varepsilon^{+hu}$ for decreasing $u$, and the wave dies out with increasing time $t$, by $\varepsilon^{-(w-f)}=\varepsilon^{-wt}\,\varepsilon^{+ft}$.

In the second wave, $i''$, $e''$, the amplitude increases in the direction of propagation, $\varepsilon^{+hu}$ for rising, $\varepsilon^{-hu}$ for decreasing $u$, but the wave dies out with the increasing time $t$, by $\varepsilon^{-(w+f)t}=\varepsilon^{-wt}\,\varepsilon^{-ft}$, that is, faster than the first wave.

If the amplitude of the wave remained constant throughout the circuit—as would be the case in a free oscillation of the circuit, in which the stored energy of the circuit is dissipated, but no power transferred one way or the other—that is, if $h=0$, it also is, by (56), $f=0$, that is, both waves coincide into one, which dies out with the time by the decrement $\epsilon^{-wt}$.

It thus follows:

In general, two waves, with their reflected waves, traverse the circuit, of which the one $i''$, $e''$, increases in amplitude in the direction of propagation, but dies out correspondingly more rapidly in time, that is, faster than a wave of constant amplitude; while the other $i'$, $e'$, decreases in amplitude, but lasts a longer time, that is, dies out slower than a wave of constant amplitude. That is, in the one wave, $i''$, $e''$, a decrease of amplitude takes place at a sacrifice of duration in time, while in the other wave, $i'$, $e'$, a slower dying out of the wave with the time is produced at the expense of a decrease of amplitude during its propagation.

It is seen herefrom, that the equations usually given for an oscillating circuit, which do not contain an exponential function of the distance, are not the most general equations, but correspond only to the special case of a free oscillation in which no energy transfer takes place, and so do not apply to the traveling wave or impulse, nor to the oscillation of a complex circuit.

6. In the equations (29) and (30):

$$q\,t = 2\,\pi$$

gives the time of a complete cycle, that is, the *period of the wave*:

$$T = \frac{2\pi}{q}$$

and:

$$N = \frac{q}{2\pi}$$

*the frequency of the wave.*

$$k\,u = 2\,\pi$$

gives the distance of a complete cycle, that is, the *wave length*:

$$\Pi = \frac{2\pi}{k}$$

$$(w - f)\,t = 1 \text{ and}$$
$$(w + f)\,t = 1$$

gives the time:

$$T_1' = \frac{1}{w - f} \text{ and}$$

$$T_1'' = \frac{1}{w + f}$$

during which the wave decreases to $1/\epsilon = .3679$ of its value, and

$$h\,u = 1$$

gives the distance:

$$U_1 = 1/h$$

over which the wave decreases to $1/\epsilon = .3679$ of its value.

That is:

$q$ is the *frequency constant* of the wave:
$k$ is the *wave length constant*:
$(w - f)$ and $(w + f)$ are the *time attenuation constants* of the wave:
$h$ is the *distance attenuation constant* of the wave:

7. If the frequency of the current and voltage is very high, thousands of cycles and more, as with traveling waves, lightning disturbances, high frequency oscillations, etc., $q$ is a very large quantity compared with $f$, $w$, $m$, $h$, $k$, and $k$ is a large quantity compared with $h$, and, by dropping terms of secondary order, the preceding equations can be simplified, and become:

$$\left.\begin{aligned} h &= f\sqrt{L\,C} \\ k &= q\sqrt{L\,C} \end{aligned}\right\} \quad (37)$$

and:

$$\left.\begin{aligned} c_1 = c_2 &= \sqrt{\frac{L}{C}} \\ c_1' = c_2' &= \frac{m}{q}\sqrt{\frac{L}{C}} = 0 \end{aligned}\right\} \quad (38)$$

Denoting:

$$\left.\begin{aligned} \sigma &= \sqrt{L\,C} \\ \varsigma &= \sqrt{\frac{L}{C}} \end{aligned}\right\} \quad (39)$$

where $\sigma$ is the reciprocal of the frequency of propagation (velocity of light), it is:

$$\left.\begin{aligned} h &= \sigma f \\ k &= \sigma q \end{aligned}\right\} \tag{40}$$

$$\left.\begin{aligned} c_1 &= c_2 = c \\ c_1' &= c_2' = \frac{m}{q} c = 0 \end{aligned}\right\} \tag{41}$$

and, introducing the new independent variable, as distance:

$$\lambda = \sigma u \tag{42}$$

it is:

$$\left.\begin{aligned} k u &= q \lambda \\ h u &= f \lambda \end{aligned}\right\} \tag{43}$$

hence, the wave length is given by:

$$q \lambda = 2 \pi$$

as:

$$\lambda_0 = \frac{2\pi}{q} \tag{44}$$

and since the period is:

$$T_0 = \frac{2\pi}{q}$$

it follows, that by the introduction of the denotation (42), distances are measured with the velocity of propagation as unit length, and wave length $U$ and period $T$ have the same numerical values.

Substituting now in equations (29) and (30), gives:

$$\left.\begin{aligned} i = \epsilon^{-wt} \Sigma \{ \epsilon^{+f(t-\lambda)} D_1 [q(t-\lambda)] - \epsilon^{+f(t+\lambda)} D_2 [q(t+\lambda)] & \quad (i') \\ + \epsilon^{-f(t-\lambda)} D_3 [q(t-\lambda)] - \epsilon^{-f(t+\lambda)} D_4 [q(t+\lambda)] \} & \quad (i'') \end{aligned}\right. \tag{45}$$

$$\left.\begin{aligned} e = \sqrt{\frac{L}{C}} \epsilon^{-wt} \Sigma \{ \epsilon^{+f(t-\lambda)} D_1 [q(t-\lambda)] + \epsilon^{+f(t+\lambda)} D_2 [q(t+\lambda)] & \quad (e') \\ + \epsilon^{-f(t-\lambda)} D_3 [q(t-\lambda)] + \epsilon^{-f(t+\lambda)} D_4 [q(t+\lambda)] \} & \quad (e'') \end{aligned}\right. \tag{46}$$

where:

$$D[q(t \pm \lambda)] = C \cos q(t \pm \lambda) + C' \sin q(t \pm \lambda) \tag{47}$$

8. As seen from equations (45) and (46), the waves are products of $\varepsilon^{-wt}$ and a function of $(t-\lambda)$ for the main wave, $(t+\lambda)$ for the reflected wave:

$$\left.\begin{aligned} i_1 + i_3 &= \varepsilon^{-wt} f_1 (t-\lambda) \\ i_2 + i_4 &= \varepsilon^{-wt} f_2 (t+\lambda) \end{aligned}\right\} \tag{48}$$

Hence, for constant $(t-\lambda)$ on the main waves, and for constant $(t+\lambda)$ on the reflected waves, it is:

$$\left.\begin{aligned} i_1 + i_3 &= B\ \varepsilon^{-wt} \\ i_2 + i_4 &= B'\, \varepsilon^{-wt} \end{aligned}\right\} \tag{49}$$

That is, during its passage along the circuit, the wave decreases by the decrement $\varepsilon^{-wt}$, or at a constant rate, independent of frequency, wave length, etc., and depending merely on the circuit constants $r$, $L$, $g$, $C$.

That is, the decrement of the traveling wave in the direction of its motion is independent of the character of the wave, as its frequency, etc.

In other words, an impulse traveling along the circuit retains its wave shape, provided that $r$, $L$, $g$, $C$, are constant.

If $r$ and $g$ increase with the frequency, as is often the case, the higher frequency waves die out faster, and the wave shape gradually smooths out in the direction of travel.

The physical meaning of the two waves $i'$ and $i''$ can best be appreciated by observing the effect of the wave when traversing a fixed point $\lambda$ of the circuit.

Consider as instance the main wave only; $i' = i_1 + i_3$; the same applies for the reflected wave.

Assuming then, that at time $t=0$, the current $I'=0$, it is, for constant $\lambda$:

$$I = D\left(\varepsilon^{-(w-f)t} - \varepsilon^{-(w+f)t}\right)$$

the amplitude of current $I$ at point $\lambda$.

As this is the difference of two exponential functions of different decrement, it follows, that as function of time $t$, $I'$ rises from 0 to a maximum and then decreases again to zero, as shown in Fig. 1, and the actual current $i$ is the oscillatory wave with $I$ as envelope.

The combination of the two waves thus represents the passage of a wave across a given point, the amplitude rising during the arrival, and decreasing again after the passage of the wave.

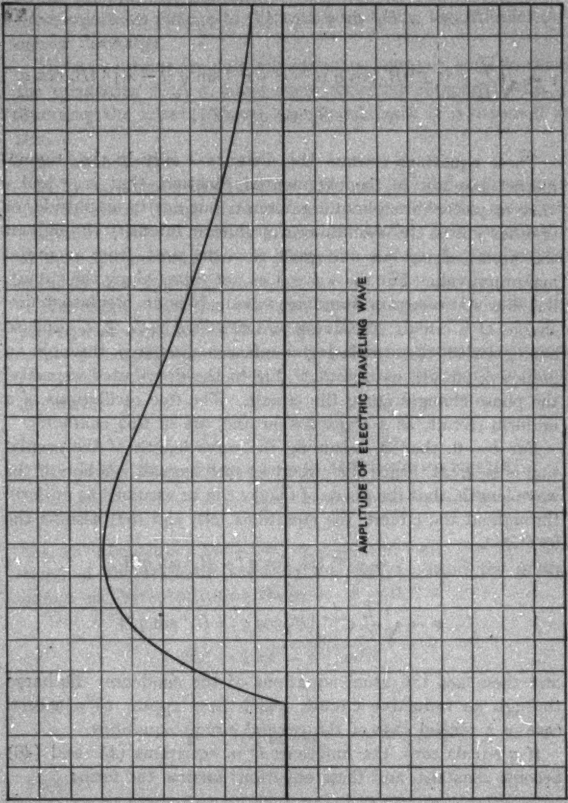

Fig. 1

9. If $h$ and also $f$ equal zero, $i'$, $e'$, and $i''$, $e''$, coincide in

equations (45) and (46), and the equations (45) (46) assume the form:

$$i = \varepsilon^{-wt} \Sigma \{[B_1 \cos q (t-\lambda) + B_1' \sin q (t-\lambda)] - [B_2 \cos q (t+\lambda) + B_2' \sin q (t+\lambda)]\} \tag{50}$$

$$e = \sqrt{\frac{L}{C}} \varepsilon^{-wt} \Sigma \{[B_1 \cos q (t-\lambda) + B_1' \sin q (t-\lambda)] + [B_2 \cos q (t+\lambda) + B_2' \sin q (t+\lambda)]\} \tag{51}$$

These equations contain the distance $\lambda$ only in the trigonometric, but not in the exponential function, that is, $i$ and $e$ vary in phase throughout the circuit, but not in amplitude, or in other words, the oscillation is of uniform intensity throughout the circuit, dying out uniformly with the time, from an initial maximum value, but the wave does not travel along the circuit, but is a stationary or standing wave. It is an oscillatory discharge of a circuit containing a distributed $r$, $L$, $g$, $C$, and so analogous to the oscillating condenser discharge through an inductive circuit, except that, due to the distributed capacity, the phase changes along the circuit. The free oscillations of a uniform circuit, as a transmission line, are of this character.

For $\lambda = 0$, that is, assuming the wave length of the oscillation is so great, hence the circuit as such a small fraction of the wave length, that the phase of $i$ and $e$ can be assumed as uniform throughout the circuit, the equations (50) and (51) assume the form:

$$i = \varepsilon^{-wt} \{B_0 \cos q t - B_0' \sin q t\}$$

$$e = \sqrt{\frac{L}{C}} \varepsilon^{-wt} \{B_0 \cos q t + B_0' \sin q t\}$$

and these are the usual equations of the condenser discharge through an inductive circuit, which here appear as a special case of a special case of the general circuit equations.

If $q$ equals zero, the functions $D$ in equations (45) and (46) become constant, and these equations assume the form:

$$i = \varepsilon^{-wt} \Sigma \{[C_1 \varepsilon^{+f(t-\lambda)} + C_2 \varepsilon^{-f(t-\lambda)}] - [C_3 \varepsilon^{+f(t+\lambda)} + C_4 \varepsilon^{-f(t+\lambda)}]\}$$

$$e = \sqrt{\frac{L}{C}} \varepsilon^{-wt} \Sigma \{[C_1 \varepsilon^{+f(t-\lambda)} + C_2 \varepsilon^{-f(t-\lambda)}] + [C_3 \varepsilon^{+f(t+\lambda)} + C_4 \varepsilon^{-f(t+\lambda)}]\}$$

This gives expressions of current and voltage, which are not oscillatory any more, but exponential, representing a gradual change of $i$ and $e$ as functions of time and distance, corresponding to the gradual or logarithmic condenser discharge. For $\lambda = 0$, these equations change to the equations of the logarithmic condenser discharge.

These equations are only approximate however, since in them the quantities $f$, $w$, $h$, have been neglected compared with $q$, assuming the latter as very large, while now it is assumed as zero.

It thus follows:

If the constant $h$ in equations (29) and (30) differs from zero, the oscillation (using the term *oscillation* here in the most general sense, that is, including also *alternation*, as an oscillation of zero attenuation) travels along the circuit; but it becomes stationary, as standing wave, for $h = 0$. That is:

The distance attenuation constant $h$ may also be called the *propagation* constant of the wave.

$h = 0$ thus represents a wave which does not propagate or move along the circuit, but stands still, that is, a stationary or standing wave.

## III. STANDING WAVES.

10. If the propagation constant of the wave vanishes:

$$h = 0$$

the wave becomes a stationary or standing wave, and the equations of the standing wave so are derived from the general equations, by substituting thereon: $h = 0$.

This gives:

$$R_2^2 = \sqrt{(k^2 - L\,C\,m^2)^2}$$

hence, if:

$$k^2 > L\,C\,m^2 \colon R_2^2 = k^2 - L\,C\,m^2,$$

and, if:

$$k^2 < L\,C\,m^2 \colon R_2^2 = L\,C\,m^2 - k^2$$

Two different cases exist, depending upon the relative values of $k^2$ and $L\,C\,m^2$, and in addition thereto the intermediary or critical case, in which $k^2 = L\,C\,m^2$.

These three cases require separate consideration.

$$L\,C\,m^2 = \left\{L\,C\,\tfrac{1}{2}\left(\frac{r}{L} - \frac{g}{C}\right)\right\}^2$$

is a circuit constant, while $k$ is the wave length constant, that is, the higher $k$, the shorter is the wave length.

A. *Short Waves*:

$$k^2 > L\,C\,m^2$$

hence:

$$R_2^2 = k^2 - L\,C\,m^2$$

and,

$$= 0$$

and approximately,

$$= \frac{k}{\sqrt{L\,C}}$$

Substituting in equations (29), (30), the two waves $i'$, $e'$, and $i''$, $e''$, coincide, and all the exponential terms reduce to $\varepsilon^{-wt}$, and rearranged, give,

$$i = \varepsilon^{-wt}\,\{[B_1 \cos(qt - ku) + B_1' \sin(qt - ku)] - [B_2 \cos(qt + ku) + B_2' \sin(qt + ku)]\} \tag{52}$$

$$e = \sqrt{\frac{L}{C}}\,\varepsilon^{-wt}\,\{[B_1 \cos(qt - ku) + B_1' \sin(qt - ku)] + [B_2 \cos(qt + ku) + B_2' \sin(qt + ku)]\} \tag{53}$$

These equations represent a *stationary electrical oscillation* or standing wave in the circuit.

B. *Long Waves*:

$$k^2 < L\,C\,m^2$$

hence:

$$R_2^2 = L\,C\,m^2 - k^2$$

and:

$$f = \sqrt{m^2 - \frac{k^2}{LC}}$$

$$q = 0$$

or approximately, for very small values of $k$:

$$f = m = \frac{1}{2}\left(\frac{r}{L} - \frac{g}{C}\right)$$

Substituting now into (29) and (30), the two waves $i'$, $e'$, and $i''$, $e''$, remain separate, having different exponential terms, $\varepsilon^{-(w-f)t}$ and $\varepsilon^{-(w+f)t}$, but in each of the two waves, the main wave and the reflected wave coincide, due to the vanishing of $q$.

$$i = \varepsilon^{-wt}\left\{(B_1 \varepsilon^{+ft} + B_2 \varepsilon^{-ft}) \cos ku - (B_1' \varepsilon^{+ft} + B_2' \varepsilon^{-ft}) \sin ku\right\} \tag{54}$$

$$e = \sqrt{\frac{L}{C}}\varepsilon^{-wt}\left\{[(m+f)\, B_1' \varepsilon^{+ft} + (m-f)\, B_2' \varepsilon^{-ft}] \cos ku + [(m+f)\, B_1 \varepsilon^{+ft} + (m-f)\, B_2 \varepsilon^{-ft}] \sin ku\right\}$$

$$= \sqrt{\frac{L}{C}}\varepsilon^{-wt}\left\{m\,[(B_1' \varepsilon^{+ft} + B_2' \varepsilon^{-ft}) \cos ku + (B_1 \varepsilon^{+ft} + B_2 \varepsilon^{-ft}) \sin ku] + f\,[(B_1' \varepsilon^{+ft} - B_2' \varepsilon^{-ft}) \cos ku + (B_1 \varepsilon^{+ft} - B_2 \varepsilon^{-ft}) \sin ku]\right\}$$

These equations represent a *gradual or exponential circuit discharge.* The distribution is a trigonometric function of the distance, that is, a wave distribution, but dies out gradually in time, or without oscillation.

C. *Critical Case*:

$$k^2 = L\, C\, m^2$$

This gives:

$$i = \varepsilon^{-wt}\left\{B \cos ku - B' \sin ku\right\}$$

$$e = \sqrt{\frac{L}{C}}\varepsilon^{-wt}\left\{B' \cos ku + B \sin ku\right\}$$

In the critical case, the wave is distributed as trigonometric function of the distance, but dies out as simple exponential function of the time.

11. An electrical standing wave can have two different forms: it can be either oscillatory in time, or exponential in time, that is, gradually changing. It is interesting to investigate the conditions under which these two different cases occur.

The transition from gradual to oscillatory, takes place at:

$$k_0^2 = m^2 L C$$

for larger values of $k$, the phenomenon is oscillatory; for smaller, exponential or gradual:

As $k$ is the wave length constant, the wave length, at which the phenomenon ceases to be oscillatory in time, and becomes a gradual dying out, is given by:

$$U_0 = \frac{2\pi}{k_0}$$

$$= \frac{2\pi}{m\sqrt{L C}}$$

In an undamped wave, that is, in a circuit of zero $r$ and zero $g$, in which no energy losses occur, the velocity of propagation is:

$$v = \frac{q}{k} = \frac{1}{\sqrt{L C}}$$

and is the velocity of light:

$$v_0 = 3 \times 10^{10}$$

if the medium has unit permeability and unit inductivity.

In an undamped circuit, this wave length $U_0$ would correspond to the frequency:

$$q_0 = \frac{k_0}{\sqrt{L C}} = m$$

hence:

$$N_0 = \frac{q_0}{2\pi} = \frac{m}{2\pi}$$

The frequency, at the wave length $U_0$, is however, zero, as at this wave length the phenomenon ceases to be oscillatory. That is:

Due to the energy losses in the circuit, by the effective resistance $r$ and effective conductance $g$, the frequency $N$ of the wave is reduced below the value corresponding to the wave length $U$, the more, the greater the wave length, until at the wave length $U_0$ the frequency becomes zero, and the phenomenon thereby non-oscillatory. This means, with increasing wave length, the velocity of propagation of the phenomenon decreases, and becomes zero at wave length $U_0$.

$$\text{If } m^2 L C = 0,\ k_0 = 0, \text{ and } U_0 = \infty,$$

that is, the standing wave is always oscillatory.

$$\text{If } m^2 L C = \infty,\ k_0 = \infty, \text{ and } U_0 = 0,$$

that is, the standing wave is always non-oscillatory, or gradually dying out.

In the former case:

$$m^2 L C = 0, \text{ or oscillatory phenomenon,}$$

it is, substituting for $m^2$ and expanding:

$$\frac{r}{g} = \frac{L}{C}$$

or:

$$r C - g L = 0$$

In the latter case:

$m^2 L C = \infty$, or non-oscillatory or exponential standing wave, it is either:

$$L = 0, \text{ or } C = 0.$$

That is:

The standing wave in a circuit is always oscillatory, regardless of its wave length, if

$$\frac{r}{g} = \frac{L}{C},$$

that is, the ratio of the energy coefficients equals the ratio of the reactive coefficients of the circuit.

The standing wave can never be oscillatory, but is always exponential, or gradually dying out, if either the inductance $L$, or the capacity $C$, vanish, that is, the circuit contains no capacity or contains no inductance. In all other cases the standing wave is oscillatory for waves shorter than the critical value $U_0 = \frac{2\pi}{k_0}$, where

$$k_0^2 = m^2 L C = \frac{1}{4} \left\{ r \sqrt{\frac{C}{L}} - g \sqrt{\frac{L}{C}} \right\}^2 \qquad (56)$$

and is exponential or gradual, for standing waves longer than the critical wave length $U_0$. Or, for $k < k_0$, the standing wave is exponential; for $k > k_0$, it is oscillatory.

The term $k_0 = m \sqrt{L C}$ takes a similar part in the theory of standing waves as the term: $r_0^2 - 4 L_0 C_0$ in the condenser discharge through an inductive circuit, that is, it separates the exponential or gradual, from trigonometric or oscillatory conditions.

The difference is, that the condenser discharge through an inductive circuit is gradual, or oscillatory, depending on the circuit constants, while in a general circuit, with the same circuit constants, in general gradual as well as oscillatory standing waves exist, the former at greater wave length, or

$$m \sqrt{L C} > k,$$

the latter for shorter wave length, or

$$m \sqrt{L C} < k,$$

An idea of the quantity $k_0$, and so the wave length $U_0$, at which the frequency of the standing wave becomes zero, or the wave non-oscillatory, and of the frequency $N_0$, which in an undamped circuit will correspond to this critical wave length $N_0$, can best be derived by considering some representative numerical instance.

### 1. *High Power High Potential Overhead Transmission Line.*

12. Assuming power to be transmitted 120 miles, at 40,000 volts between line and ground, by a three-phase system with grounded neutral, over a line consisting of copper conductors, wire No. 00 B. & S. gauge with 5 feet between conductors.

Choosing as unit length the mile, it is, approximately,

$$r = .41 \text{ ohms}$$

$$L = 1.95 \times 10^{-3}\, h$$

$$g = .25 \times 10^{-6} \text{ mho}$$

$$C = .0162 \times 10^{-6}\, f.$$

Herefrom then follows:

$$w = 113$$

$$m = 97$$

$$\sigma = \sqrt{L\,C} = 5.62 \times 10^{-6}$$

$$k_0 = m\,L\,C = 545 \times 10^{-6}$$

hence, the critical wave length:

$$U_0 = \frac{2\pi}{k_0} = 11{,}500 \text{ miles}$$

and, in an undamped circuit, this wave length would correspond to the frequency of oscillation:

$$N_0 = \frac{m}{2\pi} = 15.7 \text{ cycles per second.}$$

Since the shortest wave at which the phenomenon ceases to be oscillatory, is 11,500 miles in length, and the longest wave, which can originate in the circuit, is 4 times the length of the circuit, or 480 miles, it follows that whatever waves may originate in this circuit, are by necessity oscillatory, and non-oscillatory currents or voltages can exist in this circuit only when impressed upon it by some outside source, and then are of such great wave length, that the circuit is only an insignificant fraction of the wave, and great differences of voltage and current of non-oscillatory nature cannot exist.

Since the difference in length, between the shortest non-oscillatory wave, and the longest wave which can originate in the circuit, is so very great, it follows, that in high potential long distance transmission circuits, all phenomena which may result in considerable potential differences and differences of current throughout the circuit, are oscillatory in nature.

With a length of circuit of 120 miles, the longest standing wave, which can originate in the circuit, has the wave length:

$$U = 480 \text{ miles.}$$

and herefrom follows:

$$k = \frac{2\pi}{U} = .0134$$

$$q = \frac{k}{\sqrt{L\,C}} = 2380$$

$$N = \frac{q}{2\pi} = 380 \text{ cycles.}$$

Hence, even for the longest standing wave, which may originate in this transmission line, and still more so for shorter waves, the overtones of the fundamental wave, the approximations in paragraph 7 are justified, and it thus is:

*General Equations of Standing Waves in Long Distance Power Transmission Lines*:

$$i = \Sigma\, \varepsilon^{-wt} \{[B_1 \cos (qt-ku) + B_1' \sin (qt-ku)] - [B_2 \cos (qt+ku) + B_2' \sin (qt+ku)]\} \tag{57}$$

$$e = +\sqrt{\frac{L}{C}}\, \Sigma \varepsilon^{-wt} \{[B_1 \cos (qt-ku) + B_1' \sin (qt-ku)] + [B_2 \cos (qt+ku) + B_2' \sin (qt+ku)]\} \tag{58}$$

or:

$$e = \Sigma \varepsilon^{-wt} \{[A_1 \cos (qt+ku) + A_1' \sin (qt+ku)] + [A_2 \cos (qt-ku) + A_2' \sin (qt-ku)]\} \tag{59}$$

$$i = \sqrt{\frac{C}{L}}\, \Sigma \varepsilon^{-wt} \{[A_1 \cos (qt+ku) + A_1' \sin (qt+ku)] - [A_2 \cos (qt-ku) + A_2' \sin (qt-ku)]\} \tag{60}$$

where:

$$A_1 = -\sqrt{\frac{L}{C}}\,B_2$$

$$A_1' = -\sqrt{\frac{L}{C}}\,B_2'$$

etc.

2. *High Potential Underground Power Cable.*

13. Assuming, per mile of single conductor:

$r$ = .41 ohms.

$L = .4 \times 10^{-3}\,h.$

$g = 1 \times 10^{-6}$ mho, corresponding to a power factor of the cable charging current, at 25 cycles, of 1 per cent.

$C = .6 \times 10^{-6}\,f.$

Herefrom then follows:

$$w = 513$$

$$m = 512$$

$$\sigma = \sqrt{L\,C} = 15.5 \times 10^{-6}$$

$$k_0 = m\sqrt{L\,C} = 7.95 \times 10^{-3}$$

and, critical wave length:

$$U_0 = 790 \text{ miles},$$

and, frequency of an undamped oscillation, corresponding to $U_0$:

$$N_0 = 81.5 \text{ cycles}.$$

As seen, in an underground high potential cable, the critical wave length is very much shorter than in the overhead long distance transmission line. At the same time, however, the length of an underground cable circuit is very much shorter than that of a long distance transmission line, so that the critical wave length still is very large compared with the greatest wave length of an oscillation originating in the cable; about 10 times as great.

That is, the discussion of the possible phenomena in any overhead line applies also to the underground high potential cable circuit.

3. *Submarine Telegraph Cable.*

Choosing the values:

Length of cable, 4000 miles.

Constants per mile of conductor:

$$r = 3 \text{ ohms}$$

$$L = 1 \times 10^{-3}\, h$$

$$g = 1 \times 10^{-6} \text{ mho}$$

$$C = .1 \times 10^{-6}\, f$$

hence:

$$w = 1500$$

$$m = 1500$$

$$\sigma = L\,C = 10 \times 10^{-8}$$

$$k_0 = m\sqrt{L\,C} = 15 \times 10^{-3}$$

and:

$$U_0 = 418 \text{ miles}$$

thus:

$$N_0 = 477 \text{ cycles.}$$

That is, in a submarine cable, the critical wave length $U_0$ is relatively short, so that in long submarine cables, standing waves may appear, which are not oscillatory in time, but die out gradually. In such cables, due to their relative high resistance, the damping effect is very great, $w = 1500$, and standing waves rapidly die out.

In the investigation of the submarine cable, the complete equations must therefore be used, and $q$ cannot always be assumed as large compared with $m$ and $w$, except when dealing with local oscillations.

4. *Long Distance Overhead Telephone Circuit.*

14. Considering a telephone circuit of 1000 miles length, metallic return, consisting of two wires No. 4 B. & S. gauge, 24 in. distant from each other.

Per mile of conductor:

$$r = 1.31 \text{ ohms}$$

$$L = 1.84 \times 10^{-3}\, h$$

$$C = .0172 \times 10^{-6}\, f$$

as conductance $g$ we may assume:

(a) $g = 0$, that is, very perfect insulation, as in dry weather.

(b) $q = 2.5 \times 10^{-6}$, that is, slightly leaky lines.

(c) $g = 12 \times 10^{-6}$, that is, poor insulation, or a leaky line.

(d) $g = 40 \times 10^{-6}$, that is, extremely poor insulation, as during heavy rain.

The condition may also be investigated where the line is loaded with inductance coils, spaced so close together, that in their effect we can consider this additional inductance as uniformly distributed. Let the total inductance, per unit length, be increased by the loading coils to:

$$L_1 = 9 \times 10^{-3} h$$

or about 5 times the normal value.

Denoting then the constants of the loaded line by the index 1, it is:

| | | | (a) | (b) | (c) | (d) |
|---|---|---|---|---|---|---|
| $w$ | = | = | 356 | 429 | 706 | 1518 |
| $w_1$ | = | = | 73 | 146 | 423 | 1236 |
| $m$ | = | = | 356 | 283 | 6 | –806 |
| $m_1$ | = | = | 73 | 0 | –277 | –1090 |
| $\sigma$ | $=\sqrt{LC}$ | $= 5.03 \times 10^{-6}$ | | | | |
| $\sigma_1$ | $=\sqrt{L_1C}$ | $= 12.45 \times 10^{-6}$ | | | | |
| $k_0$ | $=m\sqrt{LC}$ | = | $2 \times 10^{-3}$ | $1.6 \times 10^{-3}$ | $33.7 \times 10^{-6}$ | $4.56 \times 10^{-3}$ |
| $k_{01}$ | $=m_1\sqrt{L_1C}$ | = | $91 \times 10^{-6}$ | 0 | $3.45 \times 10^{-3}$ | $13.5 \times 10^{-3}$ |
| $U_0$ | = | = | 3140 | 3920 | 187,000 | 1380 |
| $U_{01}$ | = | = | 69,000 | ∞ | 1820 | 464 |
| $N_0$ | = | = | 55.6 | 45 | .96 | 128 |
| $N_{01}$ | = | = | 11.6 | 0 | 44 | 173 |

Hence, in a long distance telephone line, distributed leakage up to a certain amount, increases the critical wave length, and so makes even the long wave oscillatory. Beyond this amount, leakage again decreases the wave length. Distributed inductance, as by loading the line, increases the critical wave length, if the leakage is small, but in a badly leaky line, it decreases the critical wave length, and the amount of leakage, up to which an increase of the critical wave length occurs, is less, in a loaded line, that is, in a line of higher inductance.

In other words, a moderate amount of distributed leakage improves a long distance telephone line, an excessive amount of leakage spoils it. An increase of inductance, by loading the line, improves the line, if the leakage is small, but spoils the line, if the leakage is considerable. The amount of leakage up to which improvement in the telephone line occurs, is less in a loaded than in an unloaded line, that is, a loaded telephone line requires a far better insulation than an unloaded line.

## IV. TRAVELING WAVES.

15. As seen, especially in electric power circuits, overhead or underground, the longest existing standing wave has a wave length which is so small compared with the critical wave length —where the frequency becomes zero—that the effect of the damping constant on frequency and wave length is negligible. The same obviously applies also to traveling waves, generally to a greater extent still, since traveling waves commonly are of wave lengths, which are only a small part of the length of the circuit. Usually therefore in the discussion of traveling waves, the effect of the damping constants on the frequency constant $q$ and the wave length constant $k$ can be neglected, that is, frequency and wave length assumed as independent of the energy loss in the circuit, and the equations (45) and (46) applied in dealing with the traveling wave.

In these equations, the distance traveled by the wave per second, is used as unit length, by the substitution:

$$\lambda = \sigma u$$

where:

$$\sigma = \sqrt{L C}$$

as this brings $t$ and $\lambda$ into direct comparison, and eliminates $h$ and $k$ from the equations, by the equation (43).

This gives, under the limiting conditions discussed before, the

*General Equations of the Traveling Wave*:

$$\begin{aligned} i = \varepsilon^{-wt} \{ & \varepsilon^{+f(t-\lambda)} [B_1 \cos q (t-\lambda) + B_1' \sin q (t-\lambda)] - \varepsilon^{+f(t+\lambda)} [B_2 \cos \\ & q (t+\lambda) + B_2' \sin q (t+\lambda)] + \varepsilon^{-f(t-\lambda)} [B_3 \cos q (t-\lambda) + B_3' \\ & \sin q (t-\lambda)] - \varepsilon^{-f(t+\lambda)} [B_4 \cos q (t+\lambda) + B_4' \sin q (t+\lambda)] \} \end{aligned} \tag{61}$$

$$e=\sqrt{\frac{L}{C}}\varepsilon^{-wt}\{\varepsilon^{+f(t-\lambda)}[B_1\cos q(t-\lambda)+B_1'\sin q(t-\lambda)]+\varepsilon^{+f(t+\lambda)}[B_2\cos q(t+\lambda)+B_2'\sin q(t+\lambda)]+\varepsilon^{-f(t-\lambda)}[B_3\cos q(t-\lambda)+B_3'\sin q(t-\lambda)]+\varepsilon^{-f(t+\lambda)}[B_4\cos q(t+\lambda)+B_4'\sin q(t+\lambda)]\} \tag{62}$$

or:

$$e=\varepsilon^{-wt}\{\varepsilon^{+f(t-\lambda)}[A_1\cos q(t-\lambda)+A_1'\sin q(t-\lambda)]+\varepsilon^{+f(t+\lambda)}[A_2\cos q(t+\lambda)+A_2'\sin q(t+\lambda)]+\varepsilon^{-f(t-\lambda)}[A_3\cos q(t-\lambda)+A_3'\sin q(t-\lambda)]+\varepsilon^{-f(t+\lambda)}[A_4\cos q(t+\lambda)+A_4'\sin q(t+\lambda)]\} \tag{63}$$

$$i=\sqrt{\frac{C}{L}}\varepsilon^{-wt}\{\varepsilon^{+f(t-\lambda)}[A_1\cos q(t-\lambda)+A_1'\sin q(t-\lambda)]-\varepsilon^{+f(t+\lambda)}[A_2\cos q(t+\lambda)+A_2'\sin q(t+\lambda)]+\varepsilon^{-f(t-\lambda)}[A_3\cos q(t-\lambda)+A_3'\sin q(t-\lambda)]-\varepsilon^{-f(t-\lambda)}[A_4\cos q(t+\lambda)+A_4'\sin q(t+\lambda)]\} \tag{64}$$

where:

$$w=\frac{1}{2}\left(\frac{r}{L}+\frac{g}{C}\right) \tag{65}$$

In these equations the values $A$, $B$, are integration constants, which are determined by the terminal conditions of the problem.

The terms with $(t-\lambda)$ may be considered as the main wave, the terms with $(t+\lambda)$ as the reflected wave, or inversely, depending on the direction of propagation of the wave.

16. As the traveling wave consists of a main wave, with variable $(t-\lambda)$, and a reflected wave of the same character, but moving in opposite direction, thus with the variable $(t+\lambda)$, these waves may be studied separately, and afterwards the effect of their combination investigated.

Thus, considering at first one of the waves only, that with the variable $(t-\lambda)$, it is, from equations (63) to (64):

$$\begin{aligned} e &= \varepsilon^{-wt}\{\varepsilon^{+f(t-\lambda)}[A_1\cos q(t-\lambda)+A_1'\sin q(t-\lambda)]+\varepsilon^{-f(t-\lambda)}[A_3\cos q(t-\lambda)+A_3'\sin q(t-\lambda)]\} \\ &= \varepsilon^{-wt}\{(A_1\varepsilon^{+f(t-\lambda)}+A_3\varepsilon^{-f(t-\lambda)})\cos q(t-\lambda)+(A_1'\varepsilon^{+f(t-\lambda)}+A_3'\varepsilon^{-f(t-\lambda)})\sin q(t-\lambda)\} \end{aligned} \tag{66}$$

and:

$$i = \sqrt{\frac{C}{L}}\, e$$

That is, in a single traveling wave, current and voltage are in phase with each other, and proportional to each other, with an *effective impedance*:

$$z = \frac{e}{i} = \sqrt{\frac{L}{C}}$$

This proportionality between $e$ and $i$, and coincidence of phase, obviously does not exist any more in the combination of main waves and reflected waves, since in reflection, the current reverses with the reversal of the direction of propagation, while the voltage remains in the same direction.

In equation (66), the time $t$ appears only in the term $(t-\lambda)$, except in the factor $\epsilon^{-wt}$, while the distance $\lambda$ appears only in the term $(t-\lambda)$. Substituting therefore:

$$\vartheta = t - \lambda$$

hence:

$$t = \vartheta + \lambda$$

that is, counting the time differently at any point $\lambda$, and counting it at every point of the circuit from the same point in the phase of the wave, from which the time $t$ is counted at the starting point of the wave, $\lambda = 0$, or, in other words, shifting the starting point of the counting of time, with the distance $\lambda$, it is, substituted in (66):

$$\left.\begin{aligned} e &= \epsilon^{-wt}\ \{\epsilon^{+f\vartheta}(A_1 \cos q\vartheta + A_1' \sin q\vartheta) + \epsilon^{-f\vartheta}(A_2 \cos q\vartheta \\ &\qquad + A_2' \sin q\vartheta)\} \\ &= \epsilon^{-w\lambda-}\epsilon^{w\vartheta}\ \{\epsilon^{+f\vartheta}(A_1 \cos q\vartheta + A_1' \sin q\vartheta) + \epsilon^{-f\vartheta}(A_2 \cos q \\ &\qquad \vartheta + A_2 \sin q\vartheta)\} \\ &= \epsilon^{-w\lambda}\,\epsilon^{-w\vartheta}\ \{(A_1\,\epsilon^{+f\vartheta} + A_2\,\epsilon^{-f\vartheta}) \cos q\vartheta + (A_1'\,\epsilon^{+f\vartheta} + A_2' \\ &\qquad \epsilon^{-f\vartheta}) \sin q\vartheta)\} \end{aligned}\right\} \quad (67)$$

The latter form of the equation is best suited to represent the variation of the wave, at a fixed point $\lambda$ in space, as function of the local time $\vartheta$.

The wave is the product of a term: $\varepsilon^{-w\lambda}$ which decreases with increasing distance $\lambda$, and a term:

$$\begin{aligned} e_0 &= \varepsilon^{-w\vartheta}\{\varepsilon^{+f\vartheta}(A_1 \cos q\vartheta + A_1' \sin q\vartheta) + \varepsilon^{-f\vartheta}(A_2 \cos q\vartheta + A_2' \sin q\vartheta)\} \\ &= \varepsilon^{-w\vartheta}\{(A_1\varepsilon^{+f\vartheta} + A_2\varepsilon^{-f\vartheta}) \cos q\vartheta + (A_1'\varepsilon^{+f\vartheta} + A_2'\varepsilon^{-f\vartheta}) \sin q\vartheta)\} \end{aligned} \tag{68}$$

which latter term is independent of the distance, but merely a function of the time $\vartheta$, when counting the time at any point of the line from the moment of the passage of the same phase of the wave.

Since the coefficient in the exponent of the distance decrement $\varepsilon^{-w\lambda}$, contains only the circuit constants:

$$w = \frac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right)$$

but does not contain $f$ and $q$, or the other integration constants.

It follows herefrom:

The attenuation constant of a traveling wave, and therefore the distance decrement of the wave depends upon the circuit constants $r$, $L$, $g$, $C$, only, but does not depend upon the wave length, frequency, voltage or current; hence all traveling waves in the same circuit die out at the same rate, regardless of their frequency and of their wave shape, or in other words, a complex traveling wave retains its wave shape, when traversing a circuit, and merely decreases in amplitude by the distance decrement $\varepsilon^{-w\lambda}$.

The wave attenuation is a constant of the circuit.

This obviously applies only for waves of constant velocity, that is, such waves in which $q$ is large compared with $f$, $w$, and $m$, and does not strictly apply to extremely long waves, as discussed in 13.

17. By changing the line constants, as by inserting inductance in such a manner as to give the effect of uniform distribution (loading the line), the attenuation of the wave can be reduced, that is, the wave caused to travel a greater distance $u$ with the same decrease of amplitude.

As function of the inductance $L$, the attenuation constant is a minimum for:

$$\frac{d\,w_0}{d\,L} = 0$$

hence:

$$r\,C - g\,L = 0$$

or:

$$\frac{L}{C} = \frac{r}{g}$$

and, if the conductance:

$$g = 0$$

it is:

$$L = \infty$$

Hence, in a perfectly insulated circuit, or circuit having no energy losses depending on the voltage, the attenuation decreases with increase of the inductance, that is, by "loading the line", and the more inductance is inserted, the better the telephonic transmission is.

In a leaky telephone line, increase of inductance decreases the attenuation, and so improves the telephonic transmission, up to the value of inductance,

$$L = \frac{r\,C}{g}$$

and beyond this value, inductance is harmful, by again increasing the attenuation.

For instance, if in a long distance telephone circuit per mile:

$$r = 1.31 \text{ ohms}$$
$$L = 1.84 \times 10^{-3}\, h$$
$$g = 1.0 \times 10^{-6} \text{ mho}$$
$$C = 0.0172 \times 10^{-6}\, f$$

the attenuation of a traveling wave or impulse is:

$$w_0 = 0.00217$$

hence, for a distance or length of line of $l = 2000$ miles:

$$\begin{aligned} \epsilon^{-w_0 l} &= \epsilon^{-4.34} \\ &= 0.0129 \end{aligned}$$

that is, the wave is reduced to 1.29 per cent. of its original value.

The best value of inductance is, by

$$L = \frac{r}{g} C = 0.0225\, h$$

and in this case, the attenuation constant becomes:

$$w_0 = 0.00114$$

and thus:

$$\begin{aligned} \epsilon^{-w_0 l} &= \epsilon^{-2.24} \\ &= 0.1055 \end{aligned}$$

or 10.55 per cent of the original value of the wave.

In this telephone circuit, by adding per mile an additional inductance of:

$$22.5 - 1.84 = 20.7 \text{ mh.}$$

the intensity of the arriving wave is increased from 1.29 per cent. to 10.55 per cent. or more than 8 times.

If however, in wet weather, the leakage increases to the value:

$$g = 5 \times 10^{-6}$$

in the unloaded line, it is:

$$\begin{aligned} w_0 &= 0.00282 \\ \epsilon^{-w_0 l} &= 0.0035 \end{aligned}$$

while in the loaded line, it is:

$$\begin{aligned} w_0 &= 0.00341 \\ \epsilon^{-w_0 l} &= 0.0011 \end{aligned}$$

and while with the unloaded line, the arriving wave is still 0.35 per cent. of the outgoing wave, in the loaded line, it is only 0.11 per cent.; that is, in this case, loading the line with inductance has badly spoiled telephonic communication and increased the decay of the wave more than three-fold. A loaded telephone line is much more sensitive to changes of leakage $g$, that is, to meteorological conditions.

18. The equation of the traveling wave (67):

$$e = \varepsilon^{-w\lambda} \varepsilon^{-w\vartheta} \{\varepsilon^{+f\vartheta} (A_1 \cos q \vartheta + A_1 \sin q \vartheta) + \varepsilon^{-f\vartheta} (A_2 \cos q \vartheta + A_2' \sin q \vartheta)\} \qquad (67)$$

can be reduced to the form:

$$e = \varepsilon^{-w\lambda} \{E_1 \varepsilon^{-w\vartheta_1} (\varepsilon^{+f\vartheta_1} - \varepsilon^{-f\vartheta_1}) \sin q \vartheta_1 + E_2 \varepsilon^{-w\vartheta_2} (\varepsilon^{+f\vartheta_2} - \varepsilon^{-f\vartheta_2}) \cos q \vartheta_2\} \qquad (69)$$

where:

$$\vartheta_1 = \vartheta + \gamma_1 = t - \lambda - \gamma_1$$

$$\vartheta_2 = \vartheta + \gamma_2 = t - \lambda - \gamma_2$$

Any traveling wave can be resolved into, and considered as consisting of, a combination of 2 waves: the

*Traveling Sine Wave*:

$$e_1 = E_1 \varepsilon^{-w\lambda} \varepsilon^{-w\vartheta} (\varepsilon^{+f\vartheta_1} - \varepsilon^{-f\vartheta_1}) \sin q \vartheta_1 \qquad (70)$$

*Traveling Cosine Wave*:

$$e_2 = E_2 \varepsilon^{-w\lambda} \varepsilon^{-w\vartheta_2} (\varepsilon^{+f\vartheta_2} - \varepsilon^{-f\vartheta_2}) \cos q \vartheta_2 \qquad (71)$$

Since $q$ is a large quantity compared with $w$ and $f$, the two component traveling waves, (70) and (71), differ appreciably from each other in appearance only for very small values of $\vartheta$, that is, near $\vartheta_1 = 0$ and $\vartheta_2 = 0$. The traveling sine wave rises in the first half cycle very slightly, while the traveling cosine wave rises rapidly, *i.e.*, the tangent of the angle which the wave makes with the horizontal, or $\frac{d\,e}{d\,t}$, equals 0 with the sine wave, and has a definite value with the cosine wave.

All traveling waves in an electric circuit can be resolved into constituent elements, traveling sine waves and traveling cosine waves, and the general traveling wave consists of four component waves, a sine wave, its reflected wave, a cosine wave, and its reflected wave.

The elements of the traveling wave, the traveling sine wave $e_1$, and the traveling cosine wave $e_2$, contain 4 constants:

The intensity constant: $E$

The attenuation constant: $w$ respectively $w_0$

The frequency constant: $q$

And the constant: $f$

The wave starts from zero, builds up to a maximum, and then gradually dies out, to zero at infinite time.

The absolute term of the wave, that is, the term which represents the values between which the wave oscillates, is:

$$e_0 = E\,\epsilon^{-w\lambda}\,\epsilon^{-w\vartheta}\left(\epsilon^{+f\vartheta} - \epsilon^{-f\vartheta}\right) \tag{72}$$

This term $e_0$ may be called the *amplitude* of the wave. The amplitude $e_0$ is a maximum for the value of $\vartheta$, given by:

$$\frac{d\,e_0}{d\,\vartheta} = 0$$

$$\vartheta_0 = \frac{1}{2f}\log\frac{w+f}{w-f} \tag{73}$$

and, substituting this value into the equation of the absolute term of the wave, (72), gives:

$$e_m = E\,\epsilon^{-w\lambda}\,\frac{2f}{\sqrt{w^2 - f^2}}\left(\frac{w+f}{w-f}\right)^{-\frac{w}{2f}}$$

The rate of building up of the wave, or the steepness of the wave front, is given by:

$$G_0 = \left|\frac{d\,e_0}{d\,\vartheta}\right|_{\vartheta = 0}$$

$$= 2f\,E\,\epsilon^{-w\lambda}$$

It is a maximum, that is, $\vartheta_0$ a minimum, for the value of $f$, in equation (73), given by:

$$\frac{d\,\vartheta_0}{d\,f} = 0$$

or:

$$f = 0$$

or the standing wave, which rises infinitely fast, that is, appears instantly.

The smaller therefore $f$ is, the more rapidly is the rise of the traveling wave, and $f$ may be called the *acceleration constant* of the traveling wave.

$\vartheta$ is the time counted from the beginning of the wave.

Since:

$$\vartheta = t - \lambda - \gamma$$

if we change the zero point of the distance, that is, count the distance $\lambda$ from that point of the line, at which the wave starts at time $t = 0$, or in other words, count time $t$ and distance $\lambda$ from the origin of the wave, it is:

$$\vartheta = t - \gamma$$

and the traveling wave so may be represented by:

$$\left.\begin{aligned}
&\text{The amplitude:}\\
&\qquad e_0 = E\,\varepsilon^{-wt}\left(\varepsilon^{+f\vartheta} - \varepsilon^{-f\vartheta}\right)\\
&\text{The sine wave:}\\
&\qquad e_1 = E\,\varepsilon^{-wt}\left(\varepsilon^{+f\vartheta} - \varepsilon^{-f\vartheta}\right)\sin q\,\vartheta = e_0 \sin q\,\vartheta\\
&\text{The cosine wave:}\\
&\qquad e_2 = E\,\varepsilon^{-wt}\left(\varepsilon^{+f\vartheta} - \varepsilon^{-f\vartheta}\right)\cos q\,\vartheta = e_0 \cos q\,\vartheta
\end{aligned}\right\} \quad (74)$$

and $\vartheta = t - \lambda$ can be considered as the distance, counting backwards from the wave front, or the distance counted with the point $\lambda$, which the wave has just reached, as zero point, and in opposite direction to $\lambda$, or as the time, counting from the moment of the arrival of the wave front.

Equation (74) represents the distribution of the wave along the line, at the moment $t$, or the variation of the wave with the time, at a point $\lambda$.

As seen, the wave maintains its shape, but progresses along the line, and at the same time dies out, by the time decrement $\varepsilon^{-wt}$.

19. As an instance may be considered a traveling wave of the constants:

$$w = 115$$
$$f = 45$$
$$q = 2620$$
$$E = 100$$

hence:

$$e_0 = 100\,\varepsilon^{-115t}\,(\varepsilon^{+45\vartheta} - \varepsilon^{-45\vartheta})$$

$$= 100\,\varepsilon^{-115\lambda}\,(\varepsilon^{-70\vartheta} - \varepsilon^{-160\vartheta})$$

where:

$$\vartheta = t - \lambda$$

In Fig. 2 is shown the amplitude $e_0$, as function of the distance $\lambda$, for the different values of time:

$$t = 2, 4, 8, 12, 16, 20, 24 \text{ and } 32\times 10^{-3}$$

with the maximum amplitude $e_m$, in dotted line, as envelope of the curves of $e_0$.

As seen, the amplitude of the wave gradually rises, and at the same time spreads over the line, reaching the maximum at the starting point $\lambda = 0$ at the time $t_0 = 9.2\times 10^{-3}$ sec., and then decreases again while continuing to spread over the line, until it gradually dies out.

It is interesting to note that the distribution curves of the amplitude are nearly straight lines, but also, that even in the longest power transmission line the wave has reached the end of the line, and reflection occurs, before the maximum of the wave is reached: the unit of length $\lambda$ is the distance traveled by the wave per second, or 188,000 miles, and during the rise of the wave, at the origin, from its start to the maximum, or $9.2\times 10^{-3}$ sec., the wave has traveled 1760 miles, thus the reflected wave would have returned to the origin before the maximum of the wave is reached, if the circuit is shorter than 880 miles.

Fig. 3 shows the passage of the traveling wave: $e_1 = e_0 \sin q\,\vartheta$, across a point $\lambda$ of the line, with the local time $\vartheta$ as abscissas, and the instantaneous values of $e_1$ as ordinates. The values are given for $\lambda = 0$, where $\vartheta = t$; for any other point of the line, $\lambda$, the wave shape is the same, but all the ordinates reduced by the factor $\varepsilon^{-115\lambda}$, in the proportion as shown in the dotted curve in Fig. 2.

Fig. 4 shows the beginning of the passage of the traveling wave across a point $\lambda = 0$ of the line, that is, the starting of a

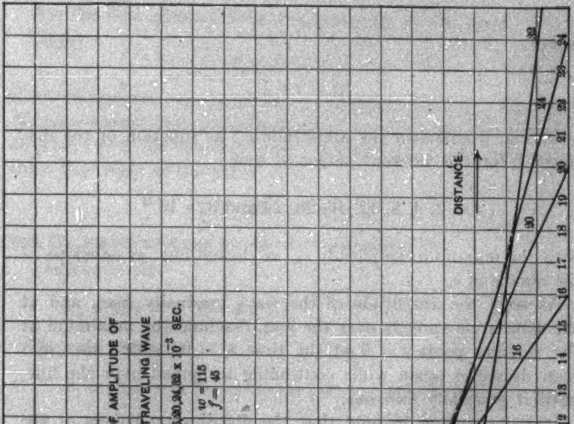
SPREAD OF AMPLITUDE OF
ELECTRIC TRAVELING WAVE
at $t = 2,4,8,12,16,20,24,32 \times 10^{-3}$ SEC.
$w = 115$
$f = 45$
DISTANCE
$10^{-3}$
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
2
4
8
12
16
20
24
32

FIG. 2

wave, or its first one and one-half cycles, for the trigonometric functions differing successively by 45 degrees, that is,

$$e_1 = e_0 \sin q\vartheta$$

$$\frac{e_1 + e_2}{\sqrt{2}} = e_0 \sin\left(q\vartheta + \frac{\pi}{4}\right)$$

$$e_2 = e_0 \cos q\vartheta = e_0 \sin\left(q\vartheta + \frac{\pi}{2}\right)$$

$$\frac{e_2 - e_1}{\sqrt{2}} = e_0 \cos\left(q\vartheta + \frac{\pi}{4}\right) = e_0 \sin\left(q\vartheta + \frac{3\pi}{4}\right)$$

the first curve of Fig. 4 so is the beginning of Fig. 3.

In waves traveling over a water surface, shapes like Fig. 4 can be observed.

For the purpose of illustration, however, in Figs. 3 and 4 the oscillations are shown far longer than usually occur: the value: $q = 2620$, corresponds to a frequency: $N = 418$ cycles, while traveling waves are more common of frequencies from 100 to 10,000 times as high.

20. A specially interesting traveling wave is the wave in which:

$$f = w$$

since in this wave the time decrement of the first main wave and its reflected wave vanishes:

$$\epsilon^{-(w-f)t} = 0$$

that is, the first main wave and its reflected wave are not transient, but permanent, that is, alternating waves, and the equations of the first main wave give the equation of the alternating-current circuit with distributed $r$, $L$, $g$, $C$, which appears as a special case of a traveling wave.

Since in this case, the frequency, and so the value of $q$ is low, and comparable with $w$ and $f$, the approximations made in the previous discussion of the traveling wave are not permissible, but the general equations have to be used.

Substituting therefore in (29) and (30):

$$f = w$$

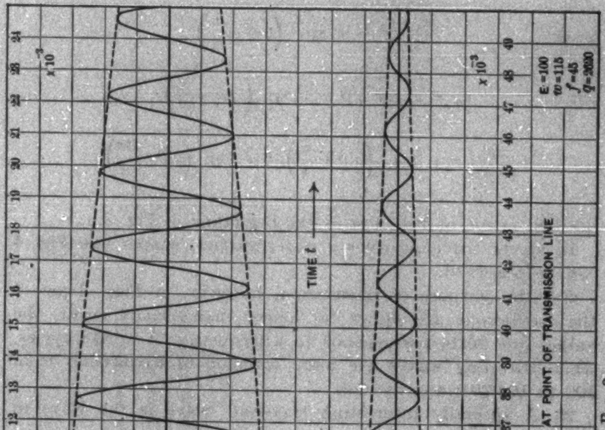
PASSAGE OF TRAVELING WAVE AT POINT OF TRANSMISSION LINE
TIME t →
MAXIMUM
E=100
w=115
f=45
q=2000
$x\,10^{-3}$
$x\,10^{-3}$
+30
+20
+10
-10
-20
-30
+10
0
-10
-20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

FIG. 3

gives:

$$i = [\varepsilon^{-hu} \{C_1 \cos (qt - ku) + C_1' \sin (qt - ku)\} - \varepsilon^{+hu} \{C_2 \cos (qt + ku) + C_2' \sin (qt + ku)\}] - \varepsilon^{-2wt} [\varepsilon^{-hu} \{C_4 \cos (qt + ku) + C_4' \sin (qt + ku)\} - \varepsilon^{+hu} \{C_3 \cos (qt - ku) + C_3' \sin (qt - ku)\}] \tag{75}$$

and:

$$e = [\varepsilon^{-hu} \{(c_1' C_1' - c_1 C_1) \cos (qt - ku) - (c_1' C_1 + c_1 C_1') \sin (qt - ku)\} + \varepsilon^{+hu} \{(c_1' C_2' - c_1 C_2) \cos (qt + ku) - (c_1' C_2 + c_1 C_2') \sin (qt + ku)\}] + \varepsilon^{-2wt} [\varepsilon^{-hu} \{(c_2' C_4' - c_2 C_4) \cos (qt + ku) - (c_2' C_4 + c_2 C_4') \sin (qt + ku)\} + \varepsilon^{+hu} \{(c_2' C_3' - c_2 C_3) \cos (qt - ku) - (c_2' C_3 + c_2 C_3') \sin (qt - ku)\}] \tag{76}$$

n these equations of current $i$ and voltage $e$, the first term represents the usual equations of the distribution of alternating current and voltage in a long distance transmission line, and can by the substitution of complex quantities be reduced to the form usually given.

The second term is a transient term of the same frequency. That is:

In a long distance transmission line or other circuits of distributed $r$, $L$, $g$, $C$, when traversed by alternating current under an alternating impressed voltage, at a change of circuit conditions a transient term of fundamental frequency may appear, which has the time decrement, that is, dies out at the rate:

$$\varepsilon^{-2wt} = \varepsilon^{-\left(\frac{r}{L} + \frac{g}{C}\right)t}$$

It is interesting to note, that here the general equations of alternating-current long distance transmission appear as a special case of the equation of the traveling wave, and indeed can be considered as a section of a traveling wave, in which the acceleration constant $f$ equals the exponential decrement $w$, and the attenuating constant $\alpha$ of the usual transmission line equation is the constant $h$; the wave length constant $\beta$ is the constant $k$.

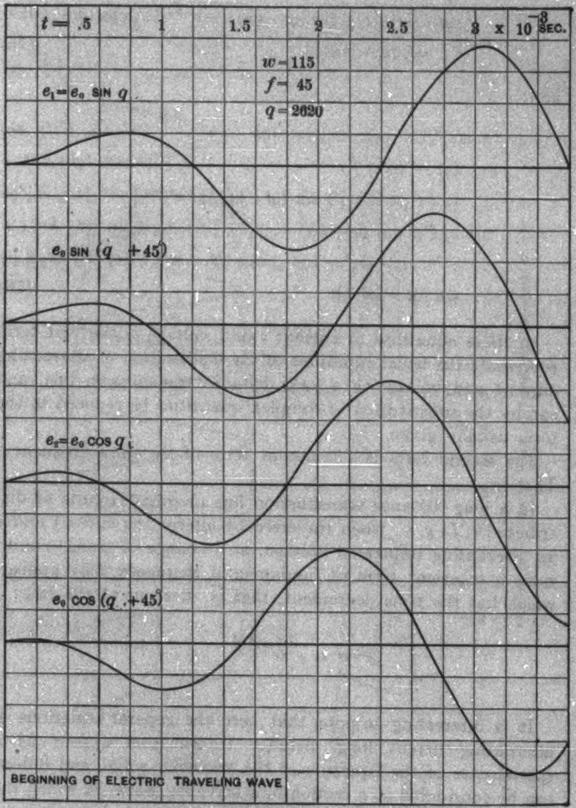
t = .5
1
1.5
2
2.5
3 x 10⁻³ SEC.
w = 115
f = 45
q = 2620
e₁ = e₀ SIN q
e₀ SIN (q + 45°)
e₂ = e₀ COS q
e₀ COS (q + 45°)
BEGINNING OF ELECTRIC TRAVELING WAVE

FIG. 4

## V. FREE OSCILLATIONS.

21. The general equations of the electric circuit (29) and (30), contain 8 terms: 4 waves, 2 main waves and their reflected waves, and each wave consists of a sine term and a cosine term.

The equations contain 5 constants:

The frequency constant $q$
The wave length constant $k$
The time attenuation constant $w$
The distance attenuation constant $k$
The time acceleration constant $f$

of which the time attenuation $w$ is a constant of the circuit, independent of the character of the wave.

By the value of the acceleration constant $f$, waves may be subdivided into:

$f = 0$: standing waves,
$w > f > 0$: traveling waves
$f = w$: alternating, current and voltage waves.

The general equations contain 8 integration constants $C$ and $C'$, which have to be determined by the terminal conditions of the problem.

Upon the values of these integration constants $C$ and $C'$ largely depends the difference between the phenomena occurring in electric circuits, as those due to direct currents or pulsating currents, alternating currents, oscillating currents, inductive discharges, etc., and the study of the *terminal conditions* is of the foremost importance.

*Free oscillations* are understood as the transient phenomena occurring in an electric circuit or part of the circuit, to which neither electric energy is supplied by some outside source, nor electric energy abstracted therefrom.

Free oscillations thus are the transient phenomena resulting from the dissipation of the energy stored in the electric field of the circuit, or inversely, the accumulation of the energy of the electric field, and their appearance so presupposes the possibility of energy storage in more than one form, so as to allow an interchange or surge of energy between its different forms, electromagnetic and electrostatic energy. Free oscillations occur only in circuits containing capacity $C$ as well as inductance $L$.

The absence of energy supply or abstraction so defines the free oscillations by the conditions, that the power $p = e\,i$ at the two ends of the circuit or section of the circuit must be zero at all times, or the circuit must be closed upon itself.

With a circuit of uniformly distributed constants, the latter case is not realized, but is of foremost importance in a complex circuit, that is, a circuit comprising sections of different constants.

Representing then the two ends of the electric circuit by $u = 0$ and $u = l$, that is, counting the distance from one end of the circuit, the condition of a free oscillation is:

$$\begin{aligned} u &= 0: & p &= 0: \\ u &= l: & p &= 0. \end{aligned}$$

since $p = e\,i$, this means that at $u = 0$ and $u = l$, either $e$ or $i$ must be zero.

This gives 4 sets of terminal conditions:

1. $e = 0$ at $u = 0$; $i = 0$ at $u = l$.
2. $i = 0$ at $u = 0$; $e = 0$ at $u = l$.
3. $e = 0$ at $u = 0$; $e = 0$ at $u = l$.
4. $i = 0$ at $u = 0$; $i = 0$ at $u = l$.

Case 2 represents the same condition as 1, merely with the distance $u$ counting from the other end of the circuit: a line open at one end, grounded at the other end. Case 3 represents a circuit open at both ends, and Case 4 a circuit grounded at both ends.

Substituting these terminal conditions into the general equations it follows:

$$h = 0$$

that is, the *free oscillation of a circuit is a standing wave.*

And also:

$$k\,l = \frac{(2\,n+1)\,\pi}{2} \tag{77}$$

if $e = 0$ at one, $i = 0$ at the other end of the circuit, and

$$k\,l = n\,\pi \tag{78}$$

if either $e = 0$ at both ends of the circuit, or $i = 0$ at both ends of the circuit.

From (77) it follows, that

$$k\,l = \frac{\pi}{2},$$

or an *odd* multiple thereof. That is, the longest wave which can exist in the circuit, is that which makes the circuit a quarter wave length. Besides this fundamental wave, all its odd multiples can exist. Such an oscillation may be called a *quarter wave oscillation.*

The oscillation of a circuit, which is open at one end, grounded at the other end, is a quarter wave oscillation, which can contain only the odd harmonics of the fundamental wave of oscillation.

From (78) it follows. that

$$k\,l = \pi$$

or a multiple thereof. That is, the longest wave, which can exist in such a circuit, is that wave, which makes the circuit a half wave length. Besides this fundamental wave, all its multiples, odd as well as even, can exist. Such an oscillation may be called a *half wave oscillation.*

The oscillations of a circuit which is open at both ends, or grounded at both ends, is a half wave oscillation, and a half wave oscillation can also contain the even harmonics of the fundamental wave of oscillation, and so also the constant term, for $n = 0$ in (78).

It is interesting to note, that in the half wave oscillation of a circuit, we have a case of a circuit, in which *even* higher harmonics exist, and the electromotive force and current wave are not symmetrical.

22. From $h = 0$ follows, by equation (35):

$$s = 0, \quad \text{if:} \quad k^2 > L\,C\,m^2,$$

and:

$$q = 0, \quad \text{if:} \quad k^2 < L\,C\,m^2,$$

The smallest value of $k$, which can exist, is, by equation (77):

$$k = \frac{\pi}{2l}$$

and, as discussed in paragraph (15), this value in high potential high power circuits usually is very much larger than $L\,C\,m^2$, so that the case: $q = 0$, is realized only in extremely long circuits, as long distance telephone or submarine cable, but not in transmission lines, and the first case: $f = 0$, is mainly of importance.

Substituting therefore: $h = 0$ and $f = 0$, dropping terms of higher order, and rearranging, finally gives the

*Equations of the Free Oscillation*:

$$\left.\begin{aligned} i &= \Sigma A\,\varepsilon^{-wt}\left\{\cos\left(qt - ku - \gamma\right) \pm \cos\left(qt + ku - \gamma\right)\right\} \\ e &= \sqrt{\frac{L}{C}}\,\Sigma\,A\,\varepsilon^{-wt}\left\{\cos\left(qt - ku - \gamma\right) \mp \cos\left(qt + ku - \gamma\right)\right\} \end{aligned}\right\} \quad (79)$$

While the free oscillation of a circuit is a standing wave, the general standing wave, as represented by equations (59) and (60), with 4 integration constants $A_1$, $A_1'$, $A_2$, $A_2'$, is not necessarily a free oscillation.

To be a free oscillation, the power $e\,i$, that is, either $e$ or $i$, must be zero at two points of the circuit, the ends of the circuit or section of circuit, which oscillates.

This gives:

$$A_1^2 + A_1'^2 = A_2^2 + A_2'^2$$

as the condition, which must be fulfilled between the integration constants, to make a standing wave a free oscillation, and as can easily be shown:

if the integration constants of a standing wave fulfil the condition:

$$A_1^2 + A_1'^2 = A_2^2 + A_2'^2 = B^2$$

the circuit of this wave contains points $u_1$, distant from each other by half a wave length, at which $e = 0$, and points $u_2$, distant from each other by half a wave length, at which $i = 0$, and the points $u_2$ are intermediate between the points $u_1$, that is, distant therefrom by one-quarter wave length. Any section of the circuit, from a point $u_1$ or $u_2$ to any other point $u_1$ or $u_2$ then is a free oscillating circuit.

In the free oscillation of the circuit, either the circuit is bounded by one point $u_1$ and one point $u_2$, that is, the voltage is zero at one end, and the current zero at the other end of the circuit, and the circuit then is a quarter wave or an odd multiple thereof, or the circuit is bounded by two points $u_1$, or by two points $u_2$, and then the voltage is zero at both ends of the circuit, or the current is zero at both ends of the circuit, and in either case the circuit is one half wave or a multiple thereof.

23. Choosing one of the points $u_1$ or $u_2$ as starting point of the distance, and introducing again the velocity of propagation as unit distance:

$$\lambda = \sigma u$$
$$\sigma = \sqrt{L C}$$

and denoting:

$$\left.\begin{aligned} \phi &= \frac{2\pi}{\lambda_0} t \\ \omega &= \frac{2\pi}{\lambda_0} \lambda = \frac{2 \pi \sqrt{L C}}{\lambda_0} u \end{aligned}\right\} \quad (80)$$

That is, representing a complete cycle of the fundamental frequency, or complete wave in time, by $\phi = 2 \pi$, and a complete wave in space, by $\omega = 2 \pi$.

A. *Quarter Wave Oscillation*:

(*a*) $e = 0$ at $u = 0$ (or: $\omega = 0$):

$$\left.\begin{aligned} e &= \varepsilon^{-ut} \sum_0^\infty {}_n B_n \sin (2 n+1) \omega \sin [(2 n+1) \phi + \gamma_n] \\ i &= \sqrt{\frac{C}{L}} \varepsilon^{-ut} \sum_0^\infty {}_n B_n \cos (2 n+1) \omega \cos [(2 n+1) \phi + \gamma_n] \end{aligned}\right\} \quad (81)$$

(*b*) $i = 0$ at $u = 0$ (or: $\omega = 0$):

$$\left.\begin{aligned} e &= \varepsilon^{-ut} \sum_0^\infty {}_n B_n \cos (2 n+1) \omega \cos [(2 n+1) \phi + \gamma_n] \\ i &= \sqrt{\frac{C}{L}} \varepsilon^{-ut} \sum_0^\infty {}_n B_n \sin (2 n+1) \omega \sin [(2 n+1) \phi + \gamma_n] \end{aligned}\right\} \quad (82)$$

B. *Half-Wave Oscillation*:

$$\left.\begin{aligned}
&(a) \qquad e = 0 \text{ at } u = 0 \text{ (or: } \omega = 0):\\
&e = \epsilon^{-wt} \sum_{0}^{\infty}{}^{n} B_n \sin n\,\omega \sin (n\,\phi + \gamma_n)\\
&i = \sqrt{\frac{C}{L}}\,\epsilon^{-wt} \sum_{0}^{\infty}{}^{n} B_n \cos n\,\omega \cos (n\,\phi + \gamma_n)
\end{aligned}\right\} \quad (83)$$

$$\left.\begin{aligned}
&(b) \qquad i = 0 \text{ at } u = 0 \text{ (or: } \omega = 0):\\
&e = \epsilon^{-wt} \sum_{0}^{\infty}{}^{n} B_n \cos n\,\omega \cos (n\,\phi + \gamma_n)\\
&i = \sqrt{\frac{C}{L}}\,\epsilon^{-wt} \sum_{0}^{\infty}{}^{n} B_n \sin n\,\omega \sin (n\,\phi + \gamma_n)
\end{aligned}\right\} \quad (84)$$

where:

$$\left.\begin{aligned}
\phi &= \frac{2\pi}{\lambda_0} t\\
\omega &= \frac{2\,\pi\,\sqrt{L\,C}}{\lambda_0} u
\end{aligned}\right\} \quad (85)$$

$$\left.\begin{aligned}
\lambda_0 &= 4\,l\,\sqrt{L\,C} \text{ in a quarter-wave,}\\
&= 2\,l\,\sqrt{L\,C} \text{ in a half-wave oscillation.}
\end{aligned}\right\} \quad (86)$$

and:

$$\epsilon^{-wt} = \epsilon^{-\frac{\lambda_0 w}{2\pi}\phi} \qquad (87)$$

$\lambda_0$ is the wave length, and thus $l/\lambda_0$ the frequency, of the fundamental wave, with the velocity of propagation as distance unit.

It is interesting to note, that the time decrement of the free oscillation, $\epsilon^{-wt}$, is the same for all frequencies and wave lengths, and that the relative intensity of the different harmonic components of the oscillation, and thereby the wave shape of the oscillation, remains unchanged during the decay of the oscillation.

This result, analogous to that found in the discussion on traveling waves, obviously is based on the assumption, that the constants of the circuit do not change with the frequency. This, however, is not perfectly true; at very high frequencies, $r$ increases, due to unequal current distribution in the conductor, and $L$ slightly decreases hereby. $g$ increases by the energy losses resulting from brush discharges and from electrostatic radiation, etc., so that in general, at very high frequency, an increase of $r/L$ and $g/C$, and so of $w$ may be expected, that is, a greater rapidity of the dying out of very high harmonics. This would result in smoothing out the wave shape with increasing decay, that is, making it more approach the fundamental and its lower harmonics.

24. The equations of a free oscillation of a circuit, as quarter wave or half wave, still contain the pairs of integration constants $B_n$ and $\gamma_n$, representing respectively the intensity and the phase of the $n$th harmonic.

These pairs of integration constants are determined by the terminal conditions of time, that is, they depend upon the amount and the distribution of the stored energy of the circuit at the starting moment of the oscillation. or in other words, on the distribution of current and voltage at $t = 0$.

The voltage $e_0$ and current $i_0$, at time $t = 0$, can be expressed as an infinite series of trigonometric functions of the distance $u$, that is, the distance angle $\omega$, or a Fourier series of such character as also to fulfil the terminal conditions in space, as discussed above, that is, $e = 0$ respectively $i = 0$ at the ends of the circuit.

The voltage and current distribution in the circuit, at the starting moment of the oscillation, $t = 0$ respectively $\phi = 0$, so determines the integration constants in the usual manner.

25. As an instance the discharge of a transmission line may be considered:

A circuit of length $l$ is charged to a uniform voltage $E$, while no current passes in the circuit. This circuit then is grounded at one end, while the other end remains insulated.

Let the distance be counted from the grounded end, and the time from the moment of grounding.

The terminal conditions then are:

(a) $\omega = 0$: $e = 0$
$\omega = \pi/2$: $i = 0$

(b) at $\phi = 0$:
$e = 0$ for: $\omega = 0$; $e = E$ for: $\omega \pm 0$
$i = 0$ for: $\omega \pm 0$; $i =$ indefinite for: $\omega = 0$.

The distribution of voltage $e_0$ and current $i_0$ in the circuit, at the starting moment $\phi = 0$, can be expressed by the Fourier series, and it is,

$$e = \frac{4\,E}{\pi} \varepsilon^{-wt} \sum_{1}^{\infty}{}_{n} \frac{\sin(2\,n+1)\,\omega \cos(2\,n+1)\,\phi}{2\,n+1}$$

$$i = \frac{4\,E}{\pi} \sqrt{\frac{C}{L}}\, \varepsilon^{-wt} \sum_{1}^{\infty}{}_{n} \frac{\cos(2\,n+1)\,\omega \sin(2\,n+1)\,\phi}{2\,n+1}$$

Choosing the constants:

$l = 120$ miles
$r = 0.41$ ohms
$L = 1.95 \times 10^{-3}\,h$
$g = 0.25 \times 10^{-6}$ mho
$C = 0.0162 \times 10^{-6}\,f$
$E = 40{,}000$ volts.

$$e = 51{,}000\, \varepsilon^{-.0485\phi} \left\{\sin\omega\cos\phi + \tfrac{1}{3}\sin 3\,\omega\cos 3\,\phi + \tfrac{1}{5}\sin 5\,\omega\cos 5\,\phi + \ldots\right\} \text{ volts}$$

$$i = 147.2\, \varepsilon^{-0.485\phi} \left\{\cos\omega\sin\phi + \tfrac{1}{3}\cos 3\,\omega\sin 3\,\phi + \tfrac{1}{5}\cos 5\,\omega\sin 5\,\phi + \ldots\right\} \text{ amperes.}$$

## VI. TRANSITION POINTS AND THE COMPLEX CIRCUIT.

26. The discussions of standing waves and free oscillations, and traveling waves, in the preceding, directly apply only to simple circuits, that is, circuits comprising a conductor of uniformly distributed constants $r, L, g, C$. Industrial electric circuits, however, never are simple circuits, but are always complex circuits comprising sections of different constants, generator, transformer, transmission lines and load; and a simple circuit is realized only by a section of a circuit, as a transmission line or a high potential transformer coil, which is cut off at both ends from the rest of the circuit, either by open circuiting: $i = 0$, or by short circuiting: $e = 0$. Approximately, the simple circuit is realized by a section of a complex circuit, connecting to other sections of very different constants, so that the ends of the circuit can, approximately, be considered as reflection points. For instance, an underground cable, of low $L$ and high $C$, when connected to a large reactive coil, of high $L$ and low $C$, may, approximately, at its ends be considered as having reflec-

tion points: $i = 0$. A high potential transformer coil, of high $L$ and low $C$, when connected to a cable, of low $L$ and high $C$, may at its ends be considered as having reflection points: $e = 0$. That is, in other words, in the first case the reactive coil may be considered as stopping the flow of current, in the latter case the cable considered as short circuiting the transformer. This approximation however, while frequently relied upon in engineering practice, and often permissible for the circuit section in which the transient phenomenon originates, is not permissible in considering the effect of the phenomenon on the adjacent sections of the circuit. For instance, in the first case above mentioned, a transient phenomenon in an underground cable connected to a high reactance: the current and voltage in the cable may approximately be represented by considering the reactive coil as a reflection point, that is, an open circuit, since only a small current enters the reactive coil. Such a small current, entering the reactive coil, may however, give a very high and destructive voltage in the reactive coil, due to its high $L$, and so in the circuit beyond the reactive coil. In the investigation of the effect of a transient phenomenon originating in one section of a complex circuit—as an oscillating arc on an underground cable—on other sections of the circuit—as the generating station—even a very great change of circuit constants, cannot be considered as a reflection point. Since this is the most important case met in industrial practice, as disturbances originating in one section of a complex circuit usually develop their destructive effects in other sections of the circuit, the investigation of the general problem of a complex circuit comprising sections of different constants becomes necessary. This requires the investigation of the changes occurring in an electric wave, and its equations, when passing over a transition point from one circuit or section of a circuit into another section of different constants.

The equations (29) and (30), while most general, are less convenient for studying the transition of a wave from one circuit to another circuit, of different constants, and since in industrial high voltage circuits at least for waves originating in the circuits, $q$ and $k$ are very large compared with $f$ and $h$, as discussed before, $f$ and $h$ may be neglected compared with $q$ and $k$. This gives the equations (45) and (46), or, substituting (47) and reversing the sign of $\lambda$, that is, counting the distance in opposite direction:

$$\begin{aligned} i = \varepsilon^{-wt} \{ & \varepsilon^{-f(\lambda-t)} [C_1 \cos q (\lambda - t) + C_1' \sin q (\lambda - t)] \\ & - \varepsilon^{+f(\lambda+t)} [C_2 \cos q (\lambda + t) + C_2' \sin q (\lambda + t)] \\ & + \varepsilon^{+f(\lambda-t)} [C_3 \cos q (\lambda - t) + C_3' \sin q (\lambda - t)] \\ & - \varepsilon^{-f(\lambda+t)} [C_4 \cos q (\lambda + t) + C_4' \sin q (\lambda + t)]\} \end{aligned} \qquad (88)$$

$$\begin{aligned} e = \sqrt{\frac{L}{C}}\, \varepsilon^{-wt} \{ & \varepsilon^{-f(\lambda-t)} [C_1 \cos q (\lambda - t) + C_1' \sin q (\lambda - t)] \\ & + \varepsilon^{+f(\lambda+t)} [C_2 \cos q (\lambda + t)) + C_2' \sin q (\lambda + t)] \\ & + \varepsilon^{+f(\lambda-t)} [C_3 \cos q (\lambda - t) + C_3' \sin q (\lambda - t)] \\ & + \varepsilon^{-f(\lambda+t)} [C_4 \cos q (\lambda + t) + C_4' \sin q (\lambda + t)]\} \end{aligned} \qquad (89)$$

where the constants are given by equations (37) to (43).

Substituting:

$$\left.\begin{aligned} C_1^2 + C_1'^2 &= A^2 \\ C_2^2 + C_2'^2 &= B^2 \\ C_3^2 + C_3'^2 &= C^2 \\ C_4^2 + C_4'^2 &= D^2 \end{aligned}\right\} \qquad (90)$$

$$\left.\begin{aligned} \frac{C_1'}{C_1} &= \tan \alpha \\ \frac{C_2'}{C_2} &= \tan \beta \\ \frac{C_3'}{C_3} &= \tan \gamma \\ \frac{C_4'}{C_4} &= \text{ta. } \delta \end{aligned}\right\} \qquad (91)$$

gives these equations in the form:

$$\begin{aligned} i = \varepsilon^{-wt} \{ & A\, \varepsilon^{-f(\lambda-t)} \cos [q (\lambda - t) - \alpha] - B\, \varepsilon^{+f(\lambda+t)} \cos [q (\lambda + t) - \beta] \\ & + C\, \varepsilon^{+f(\lambda-t)} \cos [q (\lambda - t) - \gamma] - D\, \varepsilon^{-f(\lambda+t)} \cos [q(\lambda + t) - \\ & \delta]\} \end{aligned} \qquad (92)$$

$$e=\sqrt{\frac{L}{C}}\epsilon^{-wt}\{A\,\epsilon^{-f(\lambda-t)}\cos[q(\lambda-t)-\alpha]+B\,\epsilon^{+f(\lambda+t)}\cos[q(\lambda+t)-\beta]$$
$$+C\,\epsilon^{+f(\lambda-t)}\cos[q(\lambda-t)-\gamma]+D\,\epsilon^{-f(\lambda+t)}\cos[q(\lambda+t)-\delta]\} \qquad (93)$$

In these equations, $\lambda$ is the distance co-ordinate, using the velocity of propagation as unit distance, and at a transition point from one circuit to another, where the circuit constants change, the velocity of propagation also changes, and so, for the same time, constants $f$ and $q$, $h$ and $k$, also change, and so $ku$, but transformed to the distance variable $\lambda$, $ku = q\,\lambda$ remains the same. That is, by introducing the distance variable $\lambda$, the distance can be measured throughout the entire circuit, and across transition points, at which the circuit constants change, and the same equations apply throughout the entire circuit. In this case however, in any section of the circuit,

$$\left.\begin{aligned}\lambda &= \sigma_i\,u\\ &= u\sqrt{L_i\,C_i}\end{aligned}\right\} \qquad (94)$$

where $L_i$ and $C_i$ are the inductance and the capacity, respectively, of the section $i$ of the circuit, per unit length; for instance, per mile.

That is, in a complex circuit, the time variable $t$ is the same throughout the entire circuit, or in other words, the frequency of oscillation, as represented by $q$, and the rate of decay of the oscillation, as represented by the exponential function of time must be the same throughout the entire circuit. Not so however with the distance variable $u$: the wave length of the oscillation, and its rate of building up or down, along the circuit, need not be the same, and usually are not, but in some sections of the circuit, the wave length may be far shorter, as in coiled circuits in transformers, due to the higher $L$, or in cables, due to the higher $C$. To extend the same equations over the entire complex circuit, it therefore becomes necessary to substitute for the distance variable $u$ another distance variable $\lambda$ of such character, that the wave length has the same value in all sections of the complex circuit. As the wave length of the section $i$ is $\frac{1}{\sqrt{L_i\,C_i}}$, this is done by changing the unit distance by the factor: $\sigma_i = \sqrt{L_i\,C_i}$. The distance unit of the new distance variable $\lambda$ then is the distance traversed by the wave in unit time, hence different in linear measure, for the different sections of the circuit, but offers the advantage of carrying the distance measurements across the entire circuit and over transition points, by the same distance variable $\lambda$.

This means, that the length $u_i$ of any section $i$ of the complex circuit is expressed by the length: $\lambda_i = \sigma_i u_i$.

The introduction of the distance variable $\lambda$ also has the advantage, that in the determination of the constants $r$, $L$, $g$, $C$, of the different sections of the circuit, different linear distance measurements $u$ may be used. For instance, in the transmission line, the constants may be given per mile, that is, the mile used as unit length, while in a high potential transformer coil as unit of length $u$ may be used the turn, or the coil, or the total transformer, so that the actual linear length of conductor may be unknown. For instance, choosing the total length of conductor in the high potential transformer as unit length, then the length of the transformer winding in the velocity measure $\lambda$ is, $\lambda_0 = \sqrt{L_0 C_0}$ where $L_0$ = total inductance, $C_0$ = total electrostatic capacity of transformer.

The introduction of the distant variable $\lambda$ permits the representation, in the circuit, of apparatus as reactive coils, etc., in which one of the constants is very small compared with the other, and so is usually neglected, and the apparatus considered as " massed inductance " etc., and allows the investigation of the effect of the distributed capacity of reactive coils and similar matters, by representing the reactive coil as a finite (frequently quite long) section of the circuit.

27. Let $\lambda_0, \lambda_1, \lambda_2, \ldots \lambda_n$ be a number of transition points, at which the circuit constants change, and the quantities may be denoted by index 1 in the section from $\lambda_0$ to $\lambda_1$, by index 2 in the section from $\lambda_1$ to $\lambda_2$, etc.

At $\lambda=\lambda_1$, it then must be: $i_1=i_2$, $e_1=e_2$; thus, substituting $\lambda=\lambda_1$ into equations (92) and (93), and equating, gives two identities, from which it follows:

$$w_2 \pm f_2 = w_1 \pm f_1 \tag{95}$$

that is, since $w_2 \pm w_1$, only one of the two component waves can exist. Since these two waves differ from each other only by the sign of $f$, by assuming that $f$ may be either positive or negative, we can select either one of the two waves, and the equations (92) and (93), or (88) and (89) so assume the simpler forms:

$$i = \varepsilon^{-(w+f)t} \left\{ A\, \varepsilon^{+f\lambda} \cos [q(\lambda - t) - \alpha] - B\, \varepsilon^{-f\lambda} \cos [q(\lambda + t) - \beta] \right\}$$

$$e = \sqrt{\frac{L}{C}}\, \varepsilon^{-(w+f)t} \left\{ A\, \varepsilon^{+f\lambda} \cos [q(\lambda - t) - \alpha] + B\, \varepsilon^{-f\lambda} \cos [q(\lambda + t) - \beta] \right\} \tag{96}$$

$$i = \varepsilon^{-(w+f)t} \left\{ \varepsilon^{+f\lambda} [A \cos q(\lambda - t) + B \sin q(\lambda - t)] - \varepsilon^{-f\lambda} [C \cos q(\lambda + t) + D \sin q(\lambda + t)] \right\}$$

$$e = \sqrt{\frac{L}{C}}\, \varepsilon^{-(w+f)t} \left\{ \varepsilon^{+f\lambda} [A \cos q(\lambda - t) + B \sin q(\lambda - t)] + \varepsilon^{-f\lambda} [C \cos q(\lambda + t) + D \sin q(\lambda + t)] \right\} \tag{97}$$

where $f$ may be positive or negative.

It is then:

$$w_1 + f_1 = w_2 + f_2 = w_3 + f_3 = \; . \; . \; . \; = w_n + f_n = m_0 \tag{98}$$

where $w_1$, $w_2$, $w_3$, etc., $w_n$, are the time constants of the individual sections, $\frac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right)$, and $m_0$ may be called the *resultant time decrement of the complex circuit.*

The identities: $i_1 = i_2$ and $e_1 = e_2$ for $\lambda = \lambda_1$, resolved for $\cos qt$ and $\sin qt$, then give 4 equations, by which the integration constants $A$, $B$, $\alpha$, $\beta$, or $A$, $B$, $C$, $D$, of one section of the circuit are determined by those of the adjoining section, by the expressions:

$$\left.\begin{aligned}
A_2 &= \varepsilon^{-f_2\lambda_1} \left\{ a_1\, \varepsilon^{+f_1\lambda_1} A_1 + b_1\, \varepsilon^{-f_1\lambda_1} (C_1 \cos 2\, q\, \lambda_1 + D_1 \sin 2\, q\, \lambda_1) \right\} \\
B_2 &= \varepsilon^{-f_2\lambda_1} \left\{ a_1 \; ^{+f_1\lambda_1} B_1 + b_1\, \varepsilon^{-f_1\lambda_1} (C_1 \sin 2\, q\, \lambda_1 - D_1 \cos 2\, q\, \lambda_1) \right\} \\
C_2 &= \varepsilon^{+f_2\lambda_1} \left\{ a_1\, \varepsilon^{-f_1\lambda_1} C_1 + b_1\, \varepsilon^{+f_1\lambda_1} (A_1 \cos 2\, q\, \lambda_1 - B_1 \sin 2\, q\, \lambda_1) \right\} \\
D_2 &= \varepsilon^{+f_2\lambda_1} \left\{ a_1\, \varepsilon^{-f_1\lambda_1} D_1 + b_1\, \varepsilon^{+f_1\lambda_1} (A_1 \sin 2\, q\, \lambda_1 - B_1 \cos 2\, q\, \lambda_1) \right\}
\end{aligned}\right\} \tag{99}$$

where:

$$\left.\begin{aligned} a_1 &= \frac{c_1 + c_2}{2\,c_2} \\ b_1 &= \frac{c_1 - c_2}{2\,c_2} \end{aligned}\right\} \quad (100)$$

$$\left.\begin{aligned} c_1 &= \sqrt{\frac{L_1}{C_1}} \\ c_2 &= \sqrt{\frac{L_2}{C_2}} \end{aligned}\right\} \quad (101)$$

28. The general equation of current and voltage in a complex circuit consists of two terms, a main wave and its reflected wave.

The factor $\varepsilon^{-(w+f)t} = \varepsilon^{-m_0 t}$ represents the time decrement, or the decrease of the intensity of the wave with the time, and as such is the same throughout the entire circuit. In an isolated section, of time constant $w$, the time decrement, was found however as $\varepsilon^{-wt}$. That is, with the decrement $\varepsilon^{-wt}$, the wave dies out in an isolated section at the rate at which its stored energy is dissipated by the power lost in resistance and conductance. In a section of the circuit connected to other sections, the time decrement $\varepsilon^{-m_0 t}$ does not correspond to the power dissipation in the section, that is, the wave does not die out in each section at the rate as given by the power consumed in this section, or in other words, power transfer occurs from section to section, during the oscillation of a complex circuit.

If $f$ is negative, $m_0$ is less than $w$, and the wave dies out in that particular section at a lesser rate than corresponds to the power consumed in the section, or in other words, in this section of the complex circuit, more power is consumed by $r$ and $g$ than is supplied by the decrease of the stored energy, and this section so must receive energy from adjoining sections. Inversely, if $f$ is positive, $m_0 > w$, and the wave dies out more rapidly in that section than its stored energy is consumed by $r$ and $g$; that is, a part of the stored energy of this section is transferred to the adjoining sections, and only a part—occasionally a very small part—dissipated in the section, and this section acts as a store of energy for supplying the other sections of the system.

The constant $f$ of the circuit may be called *energy transfer constant*, and positive $f$ means transfer of energy from the section to the rest of the circuit, and negative $f$ means reception of energy from other sections.

This explains the vanishing of $f$ in a standing wave of a uniform circuit, due to the absence of energy transfer, and its presence in the equations of the traveling wave, in which energy is transferred along the circuit, and in the alternating current equations.

It follows herefrom, that in a complex circuit, some of the $f$ of the different sections must always be positive, some negative.

In addition to the time decrement, $\varepsilon^{-m_0 t}$, the waves in equations (96) and (97) also contain the distance decrement $\varepsilon^{+f\lambda}$ for the main wave, $\varepsilon^{-f\lambda}$ for the reflected wave. Negative $f$ means a decrease of the main wave for increasing $\lambda$, or in the direction of propagation, and a decrease of the reflected wave for decreasing $\lambda$, that is, also in the direction of propagation, while positive $f$ means increase of main wave as well as reflected wave, in the direction of propagation along the circuit. That is if $f$ is negative, and the section so consumes more power than is given by its stored energy, and therefore receives power from the adjoining sections, the electric wave decreases, in the direction of its propagation, showing the gradual dissipation of the power received from adjoining sections. Inversely, if $f$ is positive and the section so supplies power to adjoining sections, the electric wave increases in this section, in the direction of its propagation.

In other words, in a complex circuit, in sections of low power dissipation, the wave increases, and transfers power to sections of high power dissipation in which the wave decreases.

29. Introducing the resultant time decrement $m_0$ of the complex circuit, the equations of any section can be expressed by the resultant time decrement of the entire complex circuit, $m_0$, and the energy transfer constant of the individual section:

$$f = m_0 - w \tag{102}$$

in the form:

$$i = \varepsilon^{-m_0 t} \{ \varepsilon^{+f\lambda} [A \cos q(\lambda - t) + B \sin q(\lambda - t)] - \varepsilon^{-f\lambda} [C \cos q(\lambda + t) + D \sin q(\lambda + t)] \} \tag{103}$$

$$e = \sqrt{\frac{L}{C}}\, \varepsilon^{-m_0 t} \{\varepsilon^{+l\lambda} [A \cos q\,(\lambda - t) + B \sin q\,(\lambda - t)] + \varepsilon^{-l\lambda}\, [C \cos q\,(\lambda + t) + D \sin q\,(\lambda + t)]\}$$

The constants $A$, $B$, $C$, $D$, are the integration constants, and are such as given by the terminal conditions of the problem, as by the distribution of current and voltage in the circuit at the starting moment, for $t = 0$, or at one particular point, as $\lambda = 0$.

The constants $m_0$ and $q$ are dependent upon the circuit conditions: if the circuit is closed upon itself—as usually is the case with an electrical transmission or distribution circuit—and $\Lambda$ the total length of the closed circuit, the equations must for $\lambda = \Lambda$ give the same values as for $\lambda = 0$, and therefore $q\Lambda$ must be a complete cycle or a multiple thereof: $2\,n\,\pi$. That is:

$$q = \frac{2\,n\,\pi}{\Lambda} \tag{104}$$

and the least value of $q$, or the fundamental frequency of oscillation, is:

$$q_0 = \frac{2\pi}{\Lambda} \tag{105}$$

and:

$$q = n\,q_0 \tag{106}$$

If the complex circuit is open at both ends, or grounded at both ends, and so performs a half wave oscillation, and $\Lambda_1 =$ total length of the circuit, it is:

$$\left.\begin{aligned} q_0 &= \frac{\pi}{\Lambda_1} \\ q &= n\,q_0 \end{aligned}\right. \tag{107}$$

and if the circuit is open at one end, grounded at the other end, so performing a quarter wave oscillation, and $\Lambda_2 =$ total length of circuit, it is:

$$\left.\begin{aligned} q_0 &= \frac{\pi}{2\,\Lambda_2} \\ q &= (2\,n - 1)\,q_0 \end{aligned}\right\} \tag{108}$$

If the length of the complex circuit is very great compared with the frequency of the oscillation, $q_0$ may have any value. That is, if the wave length of the oscillation is very short compared with the length of the circuit, any wave length, and so any frequency, may occur. With uniform circuits, as transmission lines, this latter case, that is, the response of the line to any frequency, can occur only in the range of very high frequencies. That is, even in a transmission line of several hundred miles length, the lowest frequency of free oscillation is fairly high, and frequencies, which are so high, compared with the fundamental frequency of the circuit, that, considered as higher harmonics thereof, they overlap, must be extremely high, of the magnitude of a million cycles. In complex circuits however, the fundamental frequency may be very much lower, and below machine frequencies, as the velocity of propagation $\frac{1}{\sqrt{L C}}$ may be quite low in some sections of the circuit, as the high potential coils of large transformers, and the presence of iron increases the inconstancy of $L$ for high frequencies, so that in such a complex circuit, even at fairly moderate frequencies, of the magnitude of 10,000 cycles, the circuit may respond to any frequency.

The constant $m_0$ also is determined by the circuit constants. Upon $m_0$ depends the energy transfer constant of the circuit section, and thereby the rate of building up, in a section of low power consumption, or building down, in a section of high power consumption. In a closed circuit, however, passing around the entire circuit, the same values of $e$ and $i$ must again be reached, and the rates of building up and building down of the wave in the different sections, must therefore be such as to neutralize each other when carried through the entire circuit, that is, the total building up, through the entire complex circuit, must be zero. This gives an equation from which $m_0$ is determined, as a mean value of the time constants $w_i$ of the individual circuit sections.

## VII. POWER AND ENERGY OF THE COMPLEX CIRCUIT.

30. The free oscillation of a complex circuit differs from that of the uniform circuit, in that the former contains exponential functions of the distance $\lambda$, which represent the shifting, or transfer of power between the sections of the circuit.

Thus the general expression of one term or frequency of current and voltage in a section of a complex circuit is given by equation:

$$i = \varepsilon^{-m_0 t} \{\varepsilon^{+f\lambda} [A \cos q (\lambda - t) + B \sin q (\lambda - t)] - \varepsilon^{-f\lambda} [C \cos q (\lambda + t) + D \sin q (\lambda + t)]\} \qquad (109)$$

$$e = \sqrt{\frac{L}{C}} \varepsilon^{-m_0 t} \{\varepsilon^{+f\lambda} [A \cos q (\lambda - t) + B \sin q (\lambda - t)] + \varepsilon^{-f\lambda} [C \cos q (\lambda + t) + D \sin q (\lambda + t)]\}$$

where:

$$q = n\, q_0$$

$$q_0 = \frac{2\pi}{\Lambda}$$

$\Lambda$ = total length of circuit. expressed in the distance coordinate:

$$\lambda = \sigma u,$$

$u$ being the distance co-ordinate of the circuit section in any measure, as miles, turns, etc., and $r$, $L$, $g$, $C$, the circuit constants per unit length of $u$, and:

$$\sigma = \sqrt{L\, C}$$

$$c = \sqrt{\frac{L}{C}}$$

$w = \frac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right)$ = time constant of circuit section,

$m_0 = w + f$ = resultant time decrement of complex circuit,
$f = m_0 - w$ = energy transfer constant of circuit section.

The instantaneous value of power at any point of the circuit, at any time $t$, is:

$$p = e\, i$$

$$= \sqrt{\frac{L}{C}} \varepsilon^{-2 m_0 t} \{\varepsilon^{+2f\lambda} [A \cos q(\lambda - t) + B \sin q(\lambda - t)]^2 - \varepsilon^{-2f\lambda} [C \cos q (\lambda + t) + D \sin q (\lambda + t)]^2\}$$

$$= \frac{1}{2}\sqrt{\frac{L}{C}} \varepsilon^{-2 m_0 t} \{[\varepsilon^{+2f\lambda} (A^2 + B^2) - \varepsilon^{-2f\lambda} (C^2 + D^2)] + [\varepsilon^{+2f\lambda} (A^2 - B^2) \cos 2 q (\lambda - t) - \varepsilon^{-2f\lambda} (C^2 - D^2) \cos 2 q (\lambda + t)] + 2 [A B \varepsilon^{+2f\lambda} \sin 2 q (\lambda - t) - C D \varepsilon^{-2f\lambda} \sin 2 q (\lambda + t)]\} \qquad (110)$$

that is, the instantaneous value of power consists of a constant term, and terms of double frequency in $(\lambda - t)$ and $(\lambda + t)$, that is, in distance $\lambda$ and time $t$.

Integrating (110) over a complete period in time, gives the *effective* or *mean value of power at any point* $\lambda$, as:

$$P = \tfrac{1}{2}\sqrt{\frac{L}{C}}\,\varepsilon^{-2m_0t}\left\{\varepsilon^{+2f\lambda}(A^2+B^2) - \varepsilon^{-2f\lambda}(C^2+D^2)\right\} \tag{111}$$

That is, the instantaneous power at any time and any point of the circuit is the difference between the instantaneous power of the main wave, and that of the reflected wave.

The effective power at any point of the circuit is the difference between the effective power of the main wave and that of the reflected wave.

The effective power at any point of the circuit, gradually decreases in any section, with the resultant time decrement of the total circuit, $\varepsilon^{-2m_0t}$, and varies gradually or exponentially with the distance $\lambda$, the one wave increasing, the other decreasing, so that at one point of the circuit or circuit section the effective power is zero. That is, this point of the circuit is a power node, or point across which no power flows. It is given by:

$$\left.\begin{aligned} &\varepsilon^{+2f\lambda}(A^2+B^2) = \varepsilon^{-2f\lambda}(C^2+D^2) \\ &\text{or:} \\ &\lambda = \frac{1}{4f}\log\frac{C^2+D^2}{A^2+B^2} \end{aligned}\right\} \tag{112}$$

The difference of power between two points of the circuit $\lambda_1$ and $\lambda_2$, that is, the power which is supplied or received (depending upon its sign) by a section $l = \lambda_2 - \lambda_1$ of the circuit, is given by equation (111) as:

$$P_0 = \tfrac{1}{2}\sqrt{\frac{L}{C}}\,\varepsilon^{-2m_0t}\left\{(\varepsilon^{+2f\lambda_2} - \varepsilon^{+2f\lambda_1})(A^2+B^2) - (\varepsilon^{-2f\lambda_2} - \varepsilon^{-2f\lambda_1})(C^2+D^2)\right\} \tag{113}$$

If $P_0 > 0$, this represents the power which is supplied by the section $l$ to the adjoining sections of the circuit; if $P_0 < 0$, this is the power received by the section from the rest of the complex circuit.

If $f\lambda_2$ and $f\lambda_1$ are small quantities, the exponential function can be resolved in an infinite series, and all but the first term dropped, as of higher orders, or negligible, and this gives the approximate value:

$$\epsilon^{\pm 2f\lambda_2} - \epsilon^{\pm 2f\lambda_1} = \pm 2f(\lambda_2 - \lambda_1) = \pm 2fl$$

hence:

$$P_0 = fl\sqrt{\frac{L}{C}}\,\epsilon^{-2m_0t}\{A^2+B^2+C^2+D^2\} \qquad (114)$$

That is, the power transferred from a section of length $l$, to the rest of the circuit, or received by the section from the rest of the circuit, is proportional to the length of the section, $l$, to its transfer constant $f$, and to the sum of the power of main wave and reflected wave.

31. The energy stored by the inductance, $L$, of a circuit element $d\lambda$, that is, in the magnetic field of the circuit, is:

$$d\eta_1 = \frac{L' i^2}{2}\,d\lambda$$

where $L'$ = inductance per unit length of circuit, expressed by the distance co-ordinate $\lambda$.

Since $L$ = inductance per unit length of circuit, of distance co-ordinate $u$, and $\lambda = \sigma u$, it is:

$$L' = \frac{L}{\sigma} = \frac{L}{\sqrt{LC}} = \sqrt{\frac{L}{C}}$$

hence:

$$d\eta_1 = \frac{1}{2}\sqrt{\frac{L}{C}}\,i^2\,d\lambda \qquad (115)$$

In general, the circuit constants $r$, $L$, $g$, $C$, per unit length, $u = 1$, give, per unit length, $\lambda = 1$, the circuit constants:

$$\left.\begin{array}{l} \dfrac{r}{\sigma};\ \dfrac{L}{\sigma};\ \dfrac{g}{\sigma};\ \dfrac{C}{\sigma}; \\ \text{or:} \\ \dfrac{r}{\sqrt{LC}};\ \dfrac{L}{\sqrt{LC}} = \sqrt{\dfrac{L}{C}};\ \dfrac{g}{\sqrt{LC}};\ \dfrac{C}{\sqrt{LC}} = \sqrt{\dfrac{C}{L}} \end{array}\right\} \qquad (116)$$

Substituting (109) in equation (115), expanded, and integrated over a complete period in time, gives the effective power stored in the magnetic field at point $\lambda$:

$$\frac{d\,H_1}{d\,\lambda} = \frac{1}{4}\sqrt{\frac{L}{C}}\,\varepsilon^{-2 m_0 t}\,\{[\varepsilon^{+2f\lambda}(A^2+B^2)+\varepsilon^{-2f\lambda}(C^2+D^2)]-2\,[(AC-BD)\cos 2\,q\,\lambda+(A\,D-B\,C)\sin 2\,q\,\lambda]\} \qquad (117)$$

and, integrated over one complete period of distance $\lambda$, or one complete wave length, this gives:

$$\frac{d\,H_1^0}{d\,\lambda} = \frac{1}{4}\sqrt{\frac{L}{C}}\,\varepsilon^{-2 m_0 t}\,\{[\varepsilon^{+2f\lambda}(A^2+B^2)+\varepsilon^{-2f\lambda}(C^2+D^2)\} \qquad (118)$$

The energy stored by the inductance $L$, or in the magnetic field of the conductor, consists of:

A constant part:

$$\frac{d\,\eta_0}{d\,\lambda} = \frac{1}{4}\sqrt{\frac{L}{C}}\,\varepsilon^{-2 m_0 t}\,\{\varepsilon^{+2f\lambda}(A^2+B^2)+\varepsilon^{-2f\lambda}(C^2+D^2)\} \qquad (119)$$

A part which is a function of $(\lambda-t)$ and $(\lambda+t)$:

$$\frac{d\,\eta'}{d\,\lambda} = \frac{1}{4}\sqrt{\frac{L}{C}}\,\varepsilon^{-2 m_0 t}\,\{[\varepsilon^{+2f\lambda}(A^2-B^2)\cos 2\,q\,(\lambda-t)+\varepsilon^{-2f\lambda}(C^2-D^2)\cos 2\,q\,(\lambda+t)]+2\,[A\,B\,\varepsilon^{+2f\lambda}\sin 2\,q\,(\lambda-t)+C\,D\,\varepsilon^{-2f\lambda}\sin 2\,q\,(\lambda+t)]\} \qquad (120)$$

A part which is a function of the distance $\lambda$ only, but not of time $t$:

$$-\frac{d\,\eta''}{d\,\lambda} = \frac{1}{2}\sqrt{\frac{L}{C}}\,\varepsilon^{-2 m_0 t}\,\{(A\,C-B\,D)\cos 2\,q\,\lambda+(A\,D+B\,C)\sin 2\,q\,\lambda\} \qquad (121)$$

And a part which is a function of time $t$ only, but not of the distance $\lambda$:

$$-\frac{d\,\eta'''}{d\,\lambda} = \frac{1}{2}\sqrt{\frac{L}{C}}\,\varepsilon^{-2 m_0 t}\,\{(A\,C+B\,D)\cos 2\,q\,t+(A\,D-B\,C)\sin 2\,q\,t\} \qquad (122)$$

and the total energy of the electromagnetic field of circuit element $d\lambda$ at time $t$ is:

$$\frac{d\eta_1}{d\lambda} = \frac{d\eta_0}{d\lambda} + \frac{d\eta'}{d\lambda} - \frac{d\eta''}{d\lambda} - \frac{d\eta'''}{d\lambda} \tag{123}$$

The energy stored in the electrostatic field of the conductor, or by the capacity $C$, is given by:

$$d\eta_2 = \frac{C' e^2}{2} d\lambda$$

or, substituting (116):

$$\frac{d\eta_2}{d\lambda} = \frac{1}{2}\sqrt{\frac{C}{L}}\, e^2 \tag{124}$$

and, substituting in (124) the value of $e$, from equation (109), gives the same expression as (123), except that the sign of the last two terms is reversed. That is:

The total energy of the electrostatic field of circuit element $d\lambda$ at time $t$ is:

$$\frac{d\eta_2}{d\lambda} = \frac{d\eta_0}{d\lambda} + \frac{d\eta'}{d\lambda} + \frac{d\eta''}{d\lambda} + \frac{d\eta'''}{d\lambda} \tag{125}$$

and, adding (123) and (125), gives the total stored energy of the electric field of the conductor:

$$\frac{d\eta}{d\lambda} = 2\left(\frac{d\eta_0}{d\lambda} + \frac{d\eta'}{d\lambda}\right) \tag{126}$$

and, integrated over a complete period of time, this gives:

$$\frac{dH}{d\lambda} = 2\frac{d\eta_0}{d\lambda} = \frac{1}{2}\sqrt{\frac{L}{C}}\,\varepsilon^{-2m_0 t}\left\{\varepsilon^{+2l\lambda}(A^2+B^2) + \varepsilon^{-2l\lambda}(C^2+D^2)\right\} \tag{127}$$

The two last terms, $\frac{d\eta''}{d\lambda}$ and $\frac{d\eta'''}{d\lambda}$, represent the energy which is transferred, or pulsates, between the electromagnetic and the electrostatic field of the circuit; and the term $\frac{d\eta'}{dt}$ represents the alternating (or rather oscillating) component of stored energy.

The energy stored by the electric field in a circuit section $l$, between $\lambda_1$ and $\lambda_2$, is given by integrating $\frac{d H}{d \lambda}$ between $\lambda_2$ and $\lambda_1$, as:

$$H = \frac{1}{4 f} \sqrt{\frac{L}{C}}\, \varepsilon^{-2 m_0 t} \left\{ (\varepsilon^{+2 f \lambda_2} - \varepsilon^{+2 f \lambda_1}) (A^2+B^2) - (\varepsilon^{-2 f \lambda_2} - \varepsilon^{-2 f \lambda_1}) (C^2+D^2) \right\} \tag{128}$$

$$H = \tfrac{1}{2} l \sqrt{\frac{L}{C}}\, \varepsilon^{-2 m_0 t} \left\{ A^2+B^2+C^2+D^2 \right\}$$

Differentiating (128) after $t$, gives the power supplied by the electric field of the circuit, as:

$$P = -\frac{d H}{d t}$$

or, more general:

$$= \frac{m_0}{2 f} \sqrt{\frac{L}{C}}\, \varepsilon^{-2 m_0 t} \left\{ (\varepsilon^{+2 f \lambda_2} - \varepsilon^{+2 f \lambda_1}) (A^2+B^2) - (\varepsilon^{-2 f \lambda_2} - \varepsilon^{-2 f \lambda_1}) (C^2+D^2) \right\} \tag{129}$$

$$= m_0 l \sqrt{\frac{L}{C}}\, \varepsilon^{-2 m_0 t} \left\{ A^2+B^2+C^2+D^2 \right\}$$

The power dissipated in the resistance: $r' \, d \lambda = \frac{r \, d \lambda}{\sqrt{L C}}$ and in the conductance: $g' \, d \lambda = \frac{g}{\sqrt{L C}} \, d \lambda$ of a conductor element $d \lambda$, and so the total power dissipated in the circuit element $d \lambda$ is, in the same manner:

$$\frac{d p_1}{d \lambda} = \frac{d p'}{d \lambda} + \frac{d p''}{d \lambda} = 4 w \left( \frac{d \eta_0}{d \lambda} + \frac{d \eta'}{d \lambda} \right) - 4 m \left( \frac{d \eta''}{d \lambda} + \frac{d \eta'''}{d \lambda} \right) \tag{130}$$

where, as before:

$$w = \frac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right)$$

$$m = \frac{1}{2}\left(\frac{r}{L} - \frac{g}{C}\right)$$

and, integrated over a complete period:

$$\frac{d P_1}{d \lambda} = 4 w \frac{d \eta_0}{d \lambda} - 4 m \frac{d \eta''}{d \lambda} \tag{131}$$

the power dissipated in the circuit contains a constant term.

$4 w \frac{d \eta_0}{d \lambda}$, and a term which is a periodic function of the distance $\lambda$:

$4 m \frac{d \eta''}{d \lambda}$, of double frequency.

Averaged over a half wave of the circuit, or a multiple thereof, the second term eliminates, and it is:

$$\frac{d P_1^0}{d \lambda} = 4 w \frac{d \eta_0}{d \lambda}$$

thus, the power dissipated in a section $l = \lambda_2 - \lambda_1$ of the circuit, is by integrating between limits $\lambda_1$ and $\lambda_2$:

$$P_1^0 = \frac{w_0}{2 f} \sqrt{\frac{L}{C}}\, \epsilon^{-2 m_0 t} \left\{ \left(\epsilon^{+2 f \lambda_2} - \epsilon^{+2 f \lambda_1}\right) (A^2 + B^2) + \left(\epsilon^{-2 f \lambda_2} - \epsilon^{-2 f \lambda_1}\right) (C^2 + D^2) \right\} \tag{132}$$

$$= w \sqrt{\frac{L}{C}}\, \epsilon^{-2 m_0 t} \left\{ A^2 + B^2 + C^2 + D^2 \right\}$$

Denoting therefore:

$$M^2 = (A^2 + B^2 + C^2 + D^2) \sqrt{\frac{L}{C}} \tag{133}$$

it is:

*Energy stored in the electric field of the circuit section of length l*:

$$H = \tfrac{1}{2} l M^2 \varepsilon^{-2 m_0 t} \tag{134}$$

*Power supplied to the conductor by the decay of the electric field of the circuit*:

$$P = m_0 l M^2 \varepsilon^{-2 m_0 t} \tag{135}$$

*Power dissipated in the circuit section l, by its effective resistance and conductance*:

$$P_1^0 = w l M^2 \varepsilon^{-2 m_0 t} \tag{136}$$

*Power transferred from the circuit section l*, to the rest of circuit:

$$P_0 = f l M^2 \varepsilon^{-2 m_0 t} \tag{137}$$

That is:

$w/m_0$ = ratio of power dissipated in the section, to that supplied to the section by the stored energy of its electric field.

$f/m_0$ = fraction of power supplied to the section by its electric field, which is transferred from the section to adjoining sections (or, if $f < 0$, received from them).

$f/w$ = ratio of power transferred to other sections, to power dissipated in the section.

$m_0 \div w + f$ is the ratio of the power supplied to the section by its electric field, dissipated in the section, and transferred from the section to adjoining sections.

These relations obviously are approximate only, and applicable to the case, where the wave length is short.

## VIII. REFLECTION AND REFRACTION AT TRANSITION POINT.

23. The general equation of the current and voltage in a section of a complex circuit is given by equations (109).

At a transition point $\lambda_1$ between section 1 and section 2, the constants change by equation (99).

Choosing now the transition point as zero point of $\lambda$, so that $\lambda < 0$ is section 1, $\lambda > 0$ is section 2, equations (99) assume the form:

$$\left.\begin{aligned} A_2 &= a_1 A_1 + b_1 C_1 \\ B_2 &= a_1 B_1 - b_1 D_1 \\ C_2 &= a_1 C_1 + b_1 A_1 \\ D_2 &= a_1 D_1 - b_1 B_1 \end{aligned}\right\} \tag{138}$$

and herefrom follows:

$$\left.\begin{aligned} c_2 (A_2^2 - C_2^2) &= c_1 (A_1^2 - C_1^2) \\ c_2 (B_2^2 - D_2^2) &= c_1 (B_1^2 - D_1^2) \end{aligned}\right\} \quad (139)$$

If now a wave in section 1, $A, B$, travels towards transition point $\lambda = 0$, at this point, a part is reflected, giving rise to the reflected wave $C, D$, in section 1, while a part is transmitted and appears as main wave, $A, B$, in section 2. The wave $C, D$, in section 2 would not exist, as it would be a wave coming towards $\lambda = 0$, from section 2, and not a part of the wave coming from section 1. In other words, we can consider the circuit as comprising two waves moving in opposite directions:

1. A main wave $A_1\, B_1$, giving a transmitted wave $A_2\, B_2$ and reflected wave $C_1\, D_1$.

2. A main wave $C_2\, D_2$, giving a transmitted wave $C_1'\, D_1'$ and reflected wave $A_2'\, B_2'$.

The waves moving towards the transition point are single main waves, $A_1\, B_1$ and $C_2\, D_2$, and

The waves moving away from the transition point are combinations of waves reflected in the section, and waves transmitted from the other section.

Considering first the main wave moving towards rising $\lambda$: in this, $C_2 = 0 = D_2$, hence, by (138):

$$\left.\begin{aligned} A_2 &= \frac{2\, c_1}{c_1 + c_2}\, A_1 \\ B_2 &= \frac{2\, c_1}{c_1 + c_2}\, B_1 \end{aligned}\right\} \quad (140)$$

Herefrom it follows:

The *main wave* in section 1:

$$\left.\begin{aligned} i_1 &= \varepsilon^{-m_0 t}\, \varepsilon^{+f_1 \lambda} \left\{ A_1 \cos q\, (\lambda - t) + B_1 \sin q\, (\lambda - t) \right\} \\ e_1 &= c_1\, \varepsilon^{-m_0 t}\, \varepsilon^{+f_1 \lambda} \left\{ A_1 \cos q\, (\lambda - t) + B_1 \sin q\, (\lambda - t) \right\} \end{aligned}\right\} \quad (141)$$

when reaching a transition point $\lambda = 0$, resolves into the *reflected wave*, turned back on section 1:

$$\left.\begin{aligned} i_1' &= -\frac{c_2 - c_1}{c_2 + c_1} \varepsilon^{-m_0 t} \varepsilon^{-f_1 \lambda} \{A_1 \cos q(\lambda + t) - B_1 \sin q(\lambda + t)\} \\ e_1' &= +\frac{c_2 - c_1}{c_2 + c_1} \varepsilon^{-m_0 t} \varepsilon^{-f_1 \lambda} \{A_1 \cos q(\lambda + t) - B_1 \sin q(\lambda + t)\} \end{aligned}\right\} \quad (142)$$

and the *transmitted wave*, which by passing over the transition point, enters section 2:

$$\left.\begin{aligned} i_2 &= \frac{2\, c_1}{c_1 + c_2} \varepsilon^{-m_0 t} \varepsilon^{+f_2 \lambda} \{A_1 \cos q\,(\lambda - t) + B_1 \sin q\,(\lambda - t)\} \\ e_2 &= c_2 \frac{2\, c_1}{c_1 + c_2} \varepsilon^{-m_0 t} \varepsilon^{+f_2 \lambda} \{A_1 \cos q(\lambda - t) + B_1 \sin q(\lambda - t)\} \end{aligned}\right\} \quad (143)$$

the reflection angle, $\tan(i_1') = -\frac{B_1}{A_1}$, is supplementary to the impact angle: $\tan(i_1) = +\frac{B_1}{A_1}$, and transmission angle: $\tan(i_2) = +\frac{B_1}{A_1}$.

Reversing the sign of $\lambda$ in the equation (142) of the reflected wave, that is, counting the distance for the reflected wave also in the direction of its propagation, and so in opposite direction to the main wave and the transmitted wave, equation (142) becomes:

$$\left.\begin{aligned} i_1'' &= +\frac{c_2 - c_1}{c_2 + c_1} \varepsilon^{-m_0 t} \varepsilon^{+f_1 \lambda'} \{A_1 \cos q\,(\lambda' - t) + B_1 \sin q \\ &\qquad (\lambda' - t)\} \\ e_1'' &= +c_1 \frac{c_2 - c_1}{c_2 + c_1} \varepsilon^{-m_0 t} \varepsilon^{+f_1 \lambda'} \{A_1 \cos q\,(\lambda' - t) + B_1 \sin q \\ &\qquad (\lambda' - t)\} \end{aligned}\right\} \quad (144)$$

and it is then:

$$\left.\begin{array}{ll} & i_2+i_1'' = i_1 \\ \text{or:} & \\ & i_1+i_1' = i_2 \\ & \frac{c_1}{c}\, e_2+e_1'' = e_1 \\ & e_1+e_1'' = e_2 \end{array}\right\} \qquad (145)$$

33. That is:

1. In a single electric wave, current and electromotive force are in phase with each other. Phase displacements between current and electromotive force can occur only in resultant waves, that is, in the combination of the main and the reflected wave, and then are a function of the distance $\lambda$, as the two waves would travel in opposite directions.

2. When reaching a transition point, a wave splits up into a reflected wave and a transmitted wave, the former returning, in opposite direction, over the same section, the latter entering the adjoining section of the circuit.

3. Reflection and transmission occur without change of the phase angle. That is, the phase of the current, and of the voltage, in the reflected wave and in the transmitted wave, at the transition point is the same as the phase of the main wave or incoming wave. Reflection and transmission with a change of phase angle can occur only by the combination of two waves traveling in opposite direction, over a circuit, that is, in a resultant wave, but not in a single wave.

4. The sum of the transmitted and the reflected current equals the main current, when considering these currents in their respective direction of propagation.

The sum of the voltage of main wave and of reflected wave, equals the voltage of the transmitted wave.

The sum of the voltage of the reflected wave, and of the voltage of the transmitted wave, reduced to the first section by the ratio of voltage transformation $\frac{c_2}{c_1}$, equals the voltage of the main wave.

5. At the transition point, so a voltage transformation occurs,

by the factor $\frac{c_2}{c_1}=\sqrt{\frac{L_2}{C_2}\,\frac{C_1}{L_1}}$, that is, the transmitted wave of voltage equals the difference between main wave and reflected wave, multiplied by the transformation ratio $\frac{c_2}{c_1}$; $e_2=\frac{c_1}{c_2}(e_1-e_1'')$. As a result thereof, in passing from one section of a circuit to another section, the voltage of the wave may decrease or may increase. If $\frac{c_2}{c_1} > 1$, that is, when passing from a section of low inductance and high capacity, into a section of high inductance and low capacity, as from a transmission line into a transformer or a reactive coil, the voltage of the wave is increased; if $\frac{c_2}{c_1} < 1$, that is, when passing from a section of high inductance and low capacity, into a section of low inductance and high capacity, as from a transformer to a transmission line, the voltage of the wave is decreased.

This explains the frequent increase to destruction voltages, when entering a station from the transmission line or cable, of an impulse or a wave, which in the transmission line is of relatively harmless voltage.

34. The same equations also apply for a wave passing the transition point in opposite direction, and combining both waves gives the total expressions of current and voltage on the two sides of the transition point.

In the neighborhood of the transition point, that is, for values $\lambda$, which are sufficiently small, so that $\epsilon^{+f\lambda}$ and $\epsilon^{-f\lambda}$ can be dropped, this gives the equations:

$$\begin{aligned} i_1 = \epsilon^{-m_0 t} \Big[ \{A_1 \cos q(\lambda - t) + B_1 \sin q(\lambda - t)\} - \frac{c_2 - c_1}{c_1 + c_2} \{A_1 \cos q \\ (\lambda + t) - B_1 \sin q(\lambda + t)\} - \frac{2\,c_2}{c_1 + c_2} \{C_2 \cos q(\lambda + t) + D_2 \\ \sin q(\lambda + t)\} \Big] \end{aligned}$$

$$\begin{aligned} e_1 = c_1 \epsilon^{-m_0 t} \Big[ \{A_1 \cos q(\lambda - t) + B_1 \sin q(\lambda - t)\} + \frac{c_2 - c_1}{c_2 + c_1} \{A_1 \cos q \\ (\lambda + t) - B_1 \sin q(\lambda + t)\} + \frac{2\,c_2}{c_1 + c_2} \{C_2 \cos q(\lambda + t) + D_2 \\ \sin q(\lambda + t)\} \Big] \end{aligned} \tag{146}$$

$$i_2 = -\epsilon^{-m_0 t}\left[\left\{C_2 \cos q\,(\lambda+t) + D_2 \sin q\,(\lambda+t)\right\} - \frac{c_1 - c_2}{c_1 + c_2}\left\{C_2 \cos q\,(\lambda - t) - D_2 \sin q\,(\lambda - t)\right\} - \frac{2\,c_1}{c_1 + c_2}\left\{A_1 \cos q\,(\lambda - t) + B_1 \sin q\,(\lambda - t)\right\}\right]$$

$$e_2 = c_2\,\epsilon^{-m_0 t}\left[\left\{C_2 \cos q\,(\lambda+t) + D_2 \sin q\,(\lambda+t)\right\} + \frac{c_1 - c_2}{c_1 + c_2}\left\{C_2 \cos q\,(\lambda - t) - D_2 \sin q\,(\lambda - t)\right\} + \frac{2\,c_1}{c_1 + c_2}\left\{A_1 \cos q\,(\lambda - t) + B_1 \sin q\,(\lambda - t)\right\}\right]$$

In these equations, the first term is the main wave, the second term its reflected wave, and the third term the wave transmitted from the adjoining section over the transition point.

Expanding and rearranging equations (146) gives as the distance phase angles of the waves:

$$\left.\begin{aligned}\tan i_1 &= \frac{c_2\left\{(B_1 - D_2)\cos qt + (A_1 + C_2)\sin qt\right\}}{(c_1 A_1 - c_2 C_2)\cos qt - (c_1 B_1 + c_2 D_2)\sin qt}\\ \tan i_2 &= \frac{c_1\left\{(B_1 - D_2)\cos qt + (A_1 + C_2)\sin qt\right\}}{(c_1 A_1 - c_2 C_2)\cos qt - (c_1 B_1 + c_2 D_2)\sin qt}\end{aligned}\right\} \quad (147)$$

hence:

$$\frac{\tan i_2}{\tan i_1} = \frac{c_1}{c_2} = \sqrt{\frac{L_1 C_2}{L_2 C_1}} \quad (148)$$

$$\left.\begin{aligned}\tan e_1 &= \frac{(c_1 B_1 + c_2 D_2)\cos qt + (c_1 A_1 - c_2 C_2)\sin qt}{c_2\left\{(A_1 + C_2)\cos qt - (B_1 - D_2)\sin qt\right\}}\\ \tan e_2 &= \frac{(c_1 B_1 + c_2 D_2)\cos qt + (c_1 A_1 - c_2 C_2)\sin qt}{c_1\left\{(A_1 + C_2)\cos qt - c_1 (B_1 - D_2)\sin qt\right\}}\end{aligned}\right\} \quad (149)$$

hence:

$$\frac{\tan e_2}{\tan e_1} = \frac{c_2}{c_1} = \sqrt{\frac{L_2 C_1}{L_1 C_2}} \quad (150)$$

That is, at a transition point the distance phase angle of the wave changes, so that the ratio of the tangent functions of the phase angles is constant, and the ratio of the tangent functions of the phase angles of the voltages is proportional, of the currents inversely proportional to the ratio of the circuit constants $c=\sqrt{\frac{L}{C}}$.

That is, transition of an electric wave or impulse, from one section of a circuit to another, takes place at a constant ratio of the tangent functions of the phase angle, which ratio is a constant of the circuit sections, between which the transition occurs.

This law is analogous to the law of refraction in optics, except that in the electric wave it is the ratio of the tangent functions, while in optics it is the ratio of the sine functions, which is constant and a characteristic of the media, between which the transition occurs.

This law so may be called the

*Law of refraction of a wave* at the boundary between two circuits, or at a transition point.

The law of refraction of an electric wave at the boundary between two media, that is, at a transition point between two circuit sections, is given by the constancy of the ratio of the tangent functions of the incoming and reflected wave.

## DISCUSSION ON "THE GENERAL EQUATIONS OF THE ELECTRIC CIRCUIT." ATLANTIC CITY, N. J., JULY 2, 1908

**Frederick Bedell:** It is unnecessary to dwell upon the great value of the work of Dr. Steinmetz in this and other papers. It might be proper that this paper be presented at one convention and discussed at another, a year or two later. The increasing value of the work of Dr. Steinmetz impresses me more and more, and looking back over his writings of ten or twelve years ago we find that to-day many of them are of even greater value than when they were written.

There is one thing to be noted particularly in this paper, and that is that Dr. Steinmetz has continually called attention to the physical significance and practical meaning of his results. We do not always find this careful rounding out of a paper. Not long ago, in looking over a mathematical paper on a subject in which I was interested, I was much disappointed to find that the paper stopped abruptly, and I was unable to find out what was the author's conclusion.

On account of the nature of this paper of Dr. Steinmetz, we can make only a few casual comments, which bring out nothing new. When we impress an electric impulse upon a circuit, we have a wave going in each direction; each wave keeps going around and around the circuit, until it dies out, and each time it goes around the circuit it gives us one of those terms in the series, which are added up, as Mr. Steinmetz has here done.

There is a physical feature to which attention might be called. We are most of us in the habit, when considering an ordinary alternating-current circuit, of thinking that the current in a series circuit is the same in all parts of the circuit, which is correct when there is no distributed capacity. In a circuit with distributed capacity, however, the current is not the same in all parts of the circuit; if we consider some point, $P$, in the circuit, the current may be going towards that point from both directions—a condition which we never have in a simple circuit without distributed capacity. This means that we are having electricity accumulated at that point. The point $P$, however, is not stationary, but travels along. We can think of this easier by analogy—by an hydraulic analogy. Considering first a pipe which is not flexible, an iron pipe, in which flows water which is not compressible; if we have a certain flow of water in one part of the pipe or circuit we have that same flow in all parts of the circuit. This construction illustrates the circuit without distributed capacity. Now let us consider, instead of a cast-iron pipe, a flexible rubber hose, and cause a series of impulses (as with a plunger) in the hose at one end; as a result of each impulse the hose will swell, and the swelling will travel along. Following the swelling there will be a contraction. Wherever there is a swelling, the water may be flowing from both directions towards the swelling;

and then it immediately flows away from the point and makes the hose contract. There is first a surplus and then a deficit of water (or electricity) and these are transmitted along the hose (or circuit).

Dr. Steinmetz called attention to the rates of decay, one with respect to time and the other with respect to distance. Suppose we have the impulses of different frequencies, or a complex wave which can be analyzed into the different component frequencies. These different frequencies, according to the equations of the paper, will be found to have different rates of decay; this is discussed in Chapters 12 and 13 of Bedell and Crehore's *Alternating Currents*. This means that if we have a complex wave impressed upon the circuit, the different components get to the receiving point at different times; one of them may get there a hundredth part of a second later than another, so that when they combine again into the resultant wave the wave form at the receiving end of the circuit and the wave form at the sending end of the circuit will be different. In power transmission this is ordinarily insignificant. When applied to telephony this change in wave form becomes significant, and these equations explain the distortion of speech on telephone lines, a case which has already been worked out in detail by Dr. Pupin.

Dr. Steinmetz speaks of the reflected wave. I would like to ask him whether he considers there is any reflected wave in a uniform circuit, in which there are the positive waves going around the circuit in one direction, and the negative waves going around the circuit in the other direction.

**Dugald C. Jackson:** The equations which Dr. Steinmetz has deduced are finely developed, comprehensively organized offsprings of the equation which was devised by Lord Kelvin in the first days of transatlantic telegraphy to analyze the problem of transmission of electric signal pulses through ocean cables of negligible self-induction. That equation was fertilized and hybridized by Heaviside until it could be applied to the problem of the transmission of telephonic speech-currents in circuits of uniformly distributed resistance, self-induction and capacity. Dr. Steinmetz has taken a third great and important step in developing equations which are applicable to complete circuits composed of sections of diverse characters and which also take adequate account of the terminal conditions or apparatus. The paper deals with the offspring of old friends in the electrical science, but the offspring are much more comprehensive and fully developed than the parents.

It has been usual to refer to a vibrating wire as a mechanical analogue of an electric circuit in either forced or natural electric oscillations,—that is, either when it is required to act under imposed pulsations or when stimulated into action and then left to carry out its own sweet will. A uniform wire however does not afford an illustration of the usual electric circuit of practice.

An electric circuit is ordinarily made up of sections of diverse electrical characters. Some of these sections may be long and some may be short, but they are almost inevitably found in the circuits of practice and their diversity of character robs the uniform wire of its usefulness as an analogue. We must therefore abandon the uniform wire for our analogue and take up a wire composed of sections of diverse character welded end to end. Sections of small resistance may be thought of as vibrating in air, others of higher resistance must be thought of as surrounded by molasses or other liquid of a density to correspond at each section with the desired resistance. In certain sections may be injected a large mass or inertia to represent high self-induction, and the elasticity from section to section must be adjusted to correspond with the desired electrostatic capacity. When this wire, made up of diverse sections of appropriate characters, is attached to abutments of suitably adjusted elasticity and inertia, it affords a true analogue of electric circuits of practice; but the analogue has become too complex to be illuminating. I have not found it possible to foresee the reactions that will occur in each section when a disturbance of particular character is put on such a wire by external means. Moreover, although uniform vibrating wires or plates, or loaded wires giving the semblance of uniform wires, have been prolifically treated in mathematical works, I have never observed a treatment adequate to predetermine the reactions in any wire of diverse sections. Dr. Steinmetz has now come to us with the formula for the electric circuit itself, which not only makes the analogue of less need but also probably at the same time gives the solution of the analogue.

The paper is reassuring and encouraging to the man who has only looked at it hastily, in that the simpler results set forth in it correspond with the phenomena that we know actually occur. For instance, as far as the telephone circuit is concerned, the effects of "loading" that Dr. Steinmetz sets down categorically as deductions from his equations, are those that are known to occur in the telephone circuit. Thus, it is known that leakage up to a certain degree and under certain conditions assists transmission of speech in a telephone circuit or the transmission of signals through an ocean cable, but that an excess of leakage beyond a point fixed by other conditions makes transmission worse. It is also well known that "loading" a telephone circuit under certain conditions materially improves the transmission of speech, but a line loaded to give admirable transmission with low leakage may afford poorer transmission than an unloaded line if the leakage becomes large. For instance, a particular loaded aerial open-wire telephone line may be good to talk over in clear weather, but let the weather get bad and the leakage become large and the loaded line is frightful to talk over; whereas 100 miles, or 150 miles of loaded underground line gives admirable transmission in all sorts of weather, because the leakage and other constants of such a line do not vary with the weather. That is the deduction Dr. Steinmetz draws from his equations. He doubtless knew these facts in advance, but they are demonstrated in his equations; and it is assuring to find that the equations do tell the truth in these simple matters, as this truthfulness supports a reliance upon their accuracy in more complex matters.

As an illustration of the fact that this paper carries us beyond what has been heretofore our frontier of knowledge, I will point out that the equations apparently enable us to understand the effects of terminal conditions on the action of circuits. As far as telephone analysis has heretofore gone, it has almost solely related to uniform circuits or to loaded circuits which are brought to the condition of substantially uniform circuits. The equations heretofore have not been able to cope successfully with the difficulties of the complete circuit including the complexities of terminal conditions, and the conditions of the telephone receiver and transmitter have been omitted from mathematical consideration or merely approximated. I believe that great advances in intercommunication by the telephone and telegraph are yet to come about from improvements of terminal conditions, and not so much from further improvements in the knowledge of line conditions. These equations of Dr. Steinmetz apparently lay the foundation for study of terminal conditions that may result in the improvements to which I refer.

I am now going to diverge for a moment and go back to a point to which I referred recently; and that is the tremendous increase in output of what is often called "pure" science, which now accompanies the advance of engineering. This paper illustrates the point. Formerly, engineers were followers of the men of scientific research, and the men of scientific research looked with some disdain upon men of the engineering industries. At the present time the engineers have caught up with and absorbed pretty much all of the accumulated output of the pure scientists, and they quickly absorb the current output as fast as it comes along. To keep the output in pure science (especially in physics and chemistry) abreast with the advance of the engineering industries, the engineers themselves have been forced to enter the field of pure research and their product must be recognized as unexcelled by that of the so-called pure scientists.

Dr. Steinmetz has set out in his paper a number of pronounced facts, and some of them illustrate how truth, when it is presented to one plainly, seems so common-sense and persuasive as to be almost axiomatic. For instance, Dr. Steinmetz calls attention to the fact that "The oscillation of a circuit, which is open at one end, grounded at the other end, is a quarter-wave oscillation, which can contain only the odd harmonics of the fundamental wave of oscillation." He further says "The oscillation of a circuit which is open at both ends, or grounded at both ends, is a half-wave oscillation, and a half-wave oscillation can also contain the even harmonics of the fundamental wave of oscillation, and so also the constant term, for $n = 0$ in (78)." That is to say, one can get a very erratic wave (compared with a sine alternating wave) when one sets up oscillations, and oscillatory waves need not be always of symmetrical half-pulses. The view that is commonly taught in the classroom explains the facts only partially. In another place there is stated a very interesting and very striking thing. After having studied some familiar equations we find the statement that " the wave shape of the oscillation remains unchanged during the decay of the oscillation." Then another very striking thing is found, where it is pointed out that " the wave does not die out in each section at the rate as given by the power consumed in this section, or in other words, power transfer occurs from section to section, during the oscillation of a complex circuit." I do not think that this had come to my mind before it was pointed out to me by Dr. Steinmetz. It seems a fact of great significance.

There are a number of other similar, clear-cut, categorical statements in the paper, which make it interesting to read even to one who does not undertake to go through the equations one by one for the purpose of getting more in the way of facts out of them.

Finally, I wish to congratulate Dr. Steinmetz upon the directness of the attack with which this paper goes at its object. The studies that have heretofore been made on this subject have been more or less of a roundabout siege. The direct assault, when it can be made, though sometimes imposing greater hardship on the attacking party, ordinarily brings greater results than a siege; or, at least it brings, as a rule, results that are more immediately and broadly useful. Dr. Steinmetz has been able to make successfully a direct attack upon the characteristics of a circuit that varies in character throughout its length. His processes are as novel as they are interesting, and I wish again to congratulate the Institute on receiving this demonstration of the great results that can follow a direct attack by mathematical analysis.

**H. L. Wallau:** I would like to ask Dr. Steinmetz one question. He mentions a voltage transformation at the transition point. If I am not mistaken he told us that at that transition point there could be but one frequency, the same on each side of the point, because the end of each section being the same point as the beginning of the next, the frequency was the same. If a voltage transformation occurs, can there be two voltages at the transition point? How does the transformation take place?

**Chas. P. Steinmetz:** As regards the reflected wave in a uniform circuit, the question Dr. Bedell brought up; if we had a perfectly uniform circuit without terminal points—a closed circuit—we could imagine a wave without a reflected wave, going around and around, provided we could produce such a wave. I cannot, however, at present see any possibility of producing such a wave, since any impulse or any action on the closed circuit would naturally produce two waves running in opposite directions from the starting point, and then either of these could be considered as the main wave, the other as the reflected wave. But in general when dealing with uniform circuits we have terminal points, because although the uniform circuit with terminal points, such as a line open at both ends, is not of very great practical importance, a perfectly uniform circuit without terminal points—that is, the line closed on itself at both ends—does not appear feasible from a practical standpoint.

As to the questions asked by Mr. Thomas, I think there is a misunderstanding. If we consider a circuit, with the generator on one end, the load on the other end, the main wave decreases from the generator toward the load, while the reflected wave decreases from the load toward the generator. That is, looking at the waves in the same direction of the circuit, from the generator toward the load, the one wave decreases, the other increases, with the distance. However, in treating of waves increasing or decreasing with the distance, I always consider them in the direction of propagation, which in the reflected wave is opposite to that of the main wave.

Considered in the direction of propagation, the character of the reflected wave thus is always the same as that of the main wave, either increasing with the distance or decreasing with the distance. The two component waves of the general equations, that which decreases with the distance, and that which increases with the distance, thus can not be a main wave and its reflected wave, but each of the two component waves comprises a main wave and its reflected wave.

Regarding the transformation of current and voltage at a transition point, this is a very interesting subject, deserving a far more extended discussion than was feasible in the paper. On the two sides of the transition point the resultant currents must be equal, and so also must be the resultant voltages. These however are the resultant of several waves, the main waves and the reflected waves, and the transformation ratio applies to the individual waves. Thus, at one side of the transition point the main wave and the reflected wave differ from those on the other side of the transition point by a constant factor, the transformation ratio, but at the same time the phase-angle on one side differs from that on the other side in such a manner that the resultant of main and reflected waves is the same at both sides of the transition point. As seen, this feature connects the phase-angles on the two sides of the transition point (hence the law of refraction) with the transformation ratio. For instance, if on one side the main wave and the reflected wave are much greater than on the other side, they are more nearly in opposition on the former side than on the latter, and therefore give the same resultant. However, as the phase-angle changes from point to point in the circuit, at some point, distant from the transition point, the main wave and the reflected wave are in phase with each other. The resultant is then their sum, and higher on the side where the individual waves are higher, Hence the maximum values of the wave-crests in the circuits on both sides of the transition point, have to each other the transformation ratio of the transition point (multiplied by the decrement of the circuit between transition point and wave crest). Thus, when transforming up at a transition point, at this point the voltage remains the same, but the higher voltage appears at the next wave-crest.

**W. S. Franklin** (by letter): I have found Mr. Steinmetz's paper on the General Equations of the Electric Circuit to be very instructive, and what I wish to say in discussing the paper relates chiefly to a method for discussing electric-wave motion which is due to Heaviside. Some time ago, in reading a treatise on optics by one of our leading specialists on that subject, I came across this statement: " To prove that any phenomenon is due to wave motion, it is sufficient to show (1) that it is periodic, and (2) that it is propagated with a finite velocity ", and immediately there came into my mind the idea of bullets from a Gatling gun, which are periodic and which are propagated with a finite velocity. The fact of the matter is that the idea of periodicity has been too much used in the discussion of wave motion. The wave pulse involves all of the important actions of wave motion, except that action which serves as a basis for the theory of the dispersion of light,* and the physics of wave motion may be developed in the simplest possible manner by considering the behavior of wave pulses; for it is certainly true, as Heaviside says, that the physics of wave motion is presented in its simplest aspects in a wave pulse, whereas the mathematical formulation of the wave pulse is extremely complicated. On the other hand, the physics of the wave train (a periodic succession of similar waves) is extremely complicated, and its mathematical formulation is fairly simple.

I have recently been engaged in the preparation of a paper on electric-wave motion on transmission lines and on the electric oscillation of transmission lines, and a few abstracts from this paper will serve to illustrate the point of view of Heaviside.

Fig. 1 shows a transmission line, initially open at both ends, one line being positively charged, the other negatively charged—both uniformly. The end of the line is suddenly short-circuited, a current is suddenly established at the end of the line, the charges on the wires disappear, and a wave sheet *W* travels in the direction of the arrow *V*, wiping out the electric field and charges completely, and establishing the magnetic field and current as it travels along. The lines of force of the magnetic field are represented by the dots and the magnetic field is directed away from the reader. When the wave sheet *W* reaches the open end of the line, the energy, which initially was electric, has been wholly converted into magnetic energy; the current, which has the same value over the whole line, is then suddenly reduced to zero at the open end, and, in being reduced to zero, it builds up a reversed charge and a reversed electric field at the extreme end of the line; and a wave sheet travels in a reversed direction along the line, wiping out magnetic field and electric current and laying down the reversed electric field and charge. When this wave sheet reaches the short-circuited end of the line, the line is uniformly charged (with zero current everywhere). The charge then suddenly disappears at the short-circuited end of the line, establishing a reversed current and a reversed magnetic field both of which are established by a wave sheet which travels towards the open end of the line. When this wave sheet reaches the open end of the line, the reversed current is suddenly reduced to zero at the open end, a wave sheet travels back to the short-circuited end and re-establishes the initial charge and initial electric field, so that when this wave sheet has reached the short-circuited end of the line, the entire system is in its initial condition and the line has performed one complete oscillation. Line resistance is ignored in this discussion.

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* The simple wave trains constituting the parts of the solar spectrum which is formed by a prism are produced by the prism and do not exist *as such* in the complex waves which enter the prism from the sun.

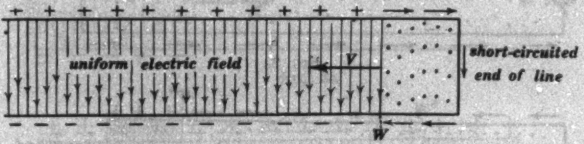

FIG. 1

Fig. 2A represents a generator delivering current over a line of negligible resistance to a receiver of negligible resistance (the system is short-circuited). The receiver end of the line is suddenly opened, the short-circuited current is suddenly reduced to zero at the opened end, and, in being reduced to zero, builds up an electric field between the lines and charges the lines, as shown in Fig. 2B (voltage assumed not to rise to a sufficiently large value to break across from line to line). The short-circuit current (and the magnetic field which corresponds to it) is wiped out by a wave sheet *W''*, and the electric field and charges are laid down by this wave sheet which travels towards the generator. A complete cycle of oscillation may easily be traced very much as in the case of Fig. 1.

A battery is suddenly connected to one end of a transmission line as shown in Fig. 3A, the other end of the transmission line being open. A wave sheet $W'$ shoots out from the battery end of the line establishing a current in the line and magnetic field between the lines, and also establishing electric charges on the lines and an electric field between them, as shown. When the wave sheet $W'$ of Fig. 3A reaches the open end of the line, the current in the line is suddenly reduced to zero, and in being reduced to zero builds up a doubled charge and doubled electric field as shown in Fig. 3B, this doubled charge and doubled electric field being established by a wave sheet $W''$ which travels back towards the battery end of the line. A complete oscillation of the line may easily be traced in this case, as in the case represented in Fig. 1.

A very interesting case is the establishment of current in a long transmission line, short-circuited at the far end, when a battery is connected to the near end, resistance being neglected. A wave sheet shoots out from the battery as represented in Fig. 3A ($I=E\sqrt{\frac{C}{L}}$, where $L$ and $C$ are line inductance and line capacity per unit of length, respectively, $E$ is the voltage of the battery, and $I$ is the current in the line behind the wave sheet). When this wave sheet reaches the short-circuited end of the line, the electric field between the wires drops to zero at the extreme end and the current rises to $2\,I$, and this doubled current and zero voltage is established over the whole line by a wave sheet which travels back towards the battery end. When this wave sheet reaches the battery end, the whole action is repeated on top of the existing short-circuit current $2\,I$. That is to say, a current $3\,I$ and battery voltage $E$ are established over the whole line by a wave sheet which shoots out from the bat-

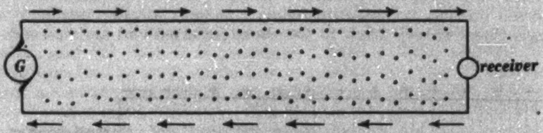

FIG. 2A

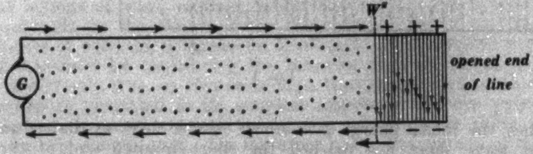

FIG. 2B

tery, and when this wave sheet reaches the short-circuited end of the line, a current 4 *I* and zero voltage are established over the whole line by a wave sheet which travels back towards the battery end. And so on. The action is precisely analogous to the surging motion of a frictionless railroad train which gets under way under a constant locomotive draw-bar pull. At the beginning, the constant pull establishes a certain velocity *I* which travels backward until it reaches the caboose; then the stretched coupling springs jerk the caboose forward and a velocity 2 *I* is established which travels forward until the whole train is moving at velocity 2 *I* with coupling springs entirely freed from stress; and then this process is repeated on top of the existing velocity 2 *I*.

A stretched string, *A B*, Fig. 4A, is pulled to one side at the

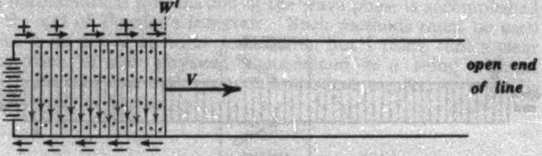

FIG. 3A

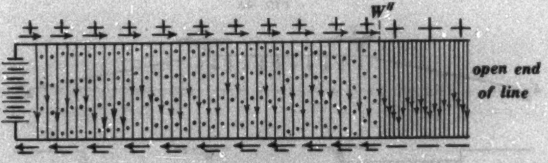

FIG. 3B

point *P*; the water at one end of a canal *C D* is held uniformly elevated and the water at the other end uniformly depressed by a gate at the center of the canal; a transmission line, *E F*, open at both ends and broken at the middle, has two batteries connected as shown, thus producing an upward electric field between the wires at one end of the line and a downward electric field between the wires at the other end of the line. The three diagrams in Fig. 4B represent the state of affairs when the initial disturbances which are represented in Fig. 4A are released. When the point *P* is released the middle portion of the string gets into motion at a uniform velocity and is entirely relieved from the stretch due to the distortion, which is represented in *A B*, Fig. 4A. The middle portion of the water in the canal immediately settles to its normal level and is set in uniform motion as represented in the diagram *C' D'*. When the switches in $E F$, Fig. 4A, are closed, the charge near the middle of the line disappears, and a uniform current (and magnetic field) is established as shown in the diagram $E' F'$. A complete cycle of oscillation may easily be followed in each case.

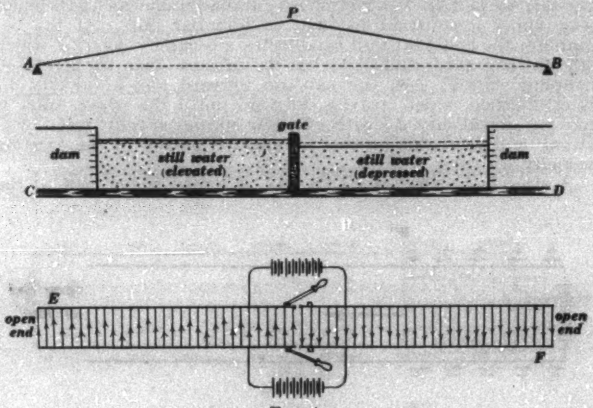
P
A
B
gate
dam
still water (elevated)
still water (depressed)
dam
C
D
E
open end
open end
F

FIG. 4A

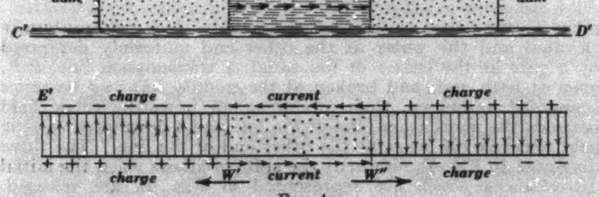
V
W'
V
W''
A'
B'
W'
W''
dam
dam
C'
D'
E'
charge
current
charge
charge
W'
current
W''
charge

FIG. 4B

The paper which I am preparing on electric-wave motion is devoted (1) to the establishment of clear ideas of the physical action which is involved in the electromagnetic wave; (2) to the discussion of a great variety of special cases; and (3) to the modification of the results so reached by the effects of line resistance and line leakage. I wish to call attention to the extremely simple discussion of electromagnetic waves which is to be found in the first volume of Heaviside's *Electromagnetic Theory*, pages 306 to 455, in which the fundamental ideas of electric-wave motion are developed on the basis of negligible attenuation (due to resistance of line and leakage between wires), and the effects of line resistance and line leakage are then described in extremely simple terms as a diffusion phenomenon modifying the results that are arrived at in the first instance. I know of no discussion of electric waves more edifying than this of Heaviside's. It would be misleading, however, if I did not mention the fact that throughout the second volume of Heaviside's *Electromagnetic Theory* the mathematical formulation is based, as it must be, upon exponential and periodic functions very much as Dr. Steinmetz has developed it, and that the mathematical formulation of the wave pulse is accomplished by the aid of Fourier's integrals. Such methods must be used if one is to arrive at numerical results, but I think that a clear conception of any physical phenomenon is a thing without which no one can make use of numerical results, or even be led to seek for them.

[illegible]

[illegible]

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# PRIMARY STANDARD OF LIGHT

BY CHARLES P. STEINMETZ

Light is not a physical quantity, but a physiological effect, that of certain wave-lengths of radiation, and therefore can not be expressed in absolute physical units; it must be measured by comparison with an arbitrarily chosen standard of physiological effect. As a result thereof, even with the best existing primary standard of light, the amylacetate lamp, the difficulties of reproduction, and maintenance of its constancy, are such as to involve errors very far beyond those considered permissible in physical measurements. A radical increase in the accuracy of reproduction and maintenance of a primary standard of light appears possible only by relating the standard of light in such manner to physical quantities, that it can be determined by energy measurements.

This led to the recommendation of defining the primary standard of light by the energy of radiation. It requires, however, a definition of the quality of radiation, since the physiological effect of radiation has no direct relation to the energy of radiation: one watt of radiation of a wave-length from the center of the visible range gives a far higher physiological effect, that is, more light, than one watt of a wave-length near the ends of the visible spectrum. This is not merely a function of the quality or color of the light, as light of the same intensity and same color, identical physiologically, may be entirely different physically, and therefore represent a different amount of power. For instance, the physiological effect of white light is produced by the combination of all colors of the spectrum, but also by an infinite number of combinations of two, three, or more spectrum colors; and these physically different forms of white light, while indistinguishable on the photometer screen, and thus physiologically identical, represent different amounts of radiation power per unit of physiological effect, or per candle-power. The same reasoning applies to colored light. The power of the visible radiation is, therefore, not a measure of light.

The definition of the absolute unit of light as the physiological effect of one watt of power of visible radiation, requires, therefore, an arbitrary definition of the distribution of power throughout the visible range. As such distribution of power through the visible range, may be chosen that of the black-body radiation at a definite temperature, and the temperature measurement may be eliminated by specifying the energy-ratio between two definite regions of the spectrum. For instance, such a definition would be:

The unit of light is that given by a black body radiating one watt of power between the wave-length of 39 and 72, under the condition (that is, at the temperature) where the power of radiation from wave length 39 to 55 bears to that from 55 to 72 the ratio $a$.

It does not appear to me that such a standard would be very satisfactory, and for the following reasons:

1. Though the intensity of radiation at the red end of the spectrum is very high, the physiological effect is very small, and an inaccuracy at this limit would therefore seriously affect the result.

2. The absorption constant of glass or any other envelope is different for different wave-lengths.

3. Any deviation of the radiator from the black-body radiation vitiates the result.

4. The color of the light would not be white, but yellow, due to the temperature limitation imposed by the radiator.

A more satisfactory primary standard of light, based on measurement of radiation power can, as I believe, be produced by selecting three primary colors of the visible spectrum. Let these colors be of definite wave-length, about equidistant from each other, and of such character that they can be absolutely reproduced at high intensity, as the spectrum lines of a luminous gas or vapor. Then define the unit of light as that given by one watt of power radiated at these three wave-lengths, in definite proportions, chosen so as to give white, or yellowish-white, light. That is, the primary unit of light is the physiological effect, as observed on the white photometer screen, of one watt of power, radiated in the three definite wave-lengths $A$, $B$, $C$. in the proportion $a \div b \div c$.

The adoption of this standard of light would eliminate the sources of error which now affect the primary flame-standard. The radiation density or light flux intensity of the three primary colors is measured separately before they are combined on the same photometer screen, and the accuracy of determination would be limited only by that of physical measurement of radiation energy, by bolometer or otherwise.

This standard of light requires three sources of monochromatic radiation, which can be maintained constant with any desired exactness. This requirement seems fulfilled by the mercury lamp. When reasonably protected from air drafts, changes of surrounding temperatures, etc., the intensity of radiation of a mercury lamp remains extremely constant at constant current, and, for minor variations of current, varies directly as the current, while that of the incandescent lamp varies as a high power of the current. It must be considered that a reproduction of the same intensity in the lamp is not required, as is the case with standard lamps, since the mercury lamp is merely the source of monochromatic light, and its intensity is measured and adjusted.

I should therefore recommend mercury lamps as the sources of the three monochromatic radiations, which combined give the primary standard of light.

Approximately, some of the brighter lines of the mercury spectrum are shown in Fig. 1 in geometric scale; that is, with the logarithm of wave-length as abscissas. When investigating the combination of different frequencies to a resultant effect, this rational scale, which is the scale of acoustics, is preferable.*

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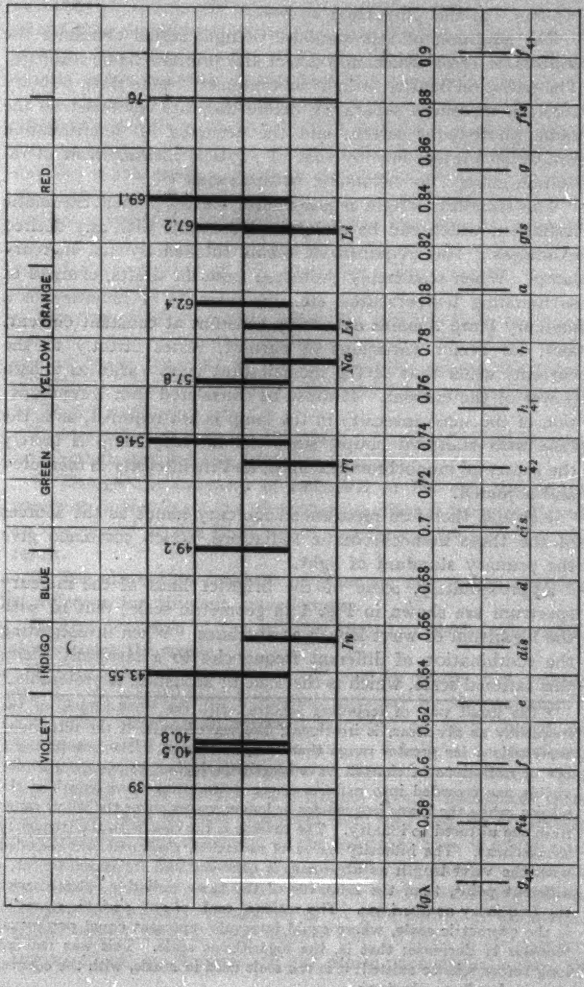
* The usual way of recording spectra, with the wave-length, or the frequency as abscissas, is irrational; one wave-length in the ultraviolet represents a far greater range than in the ultrared. The infinite number of radiations of shorter wave-length, or higher frequency than the visible, are crowded into a finite space, when using wave-length as abscissas, while the lower frequencies or longer waves cover the whole range from the ultrared to infinity. The reverse is the case with the frequency as abscissas. The intensity curve of radiation, measured and recorded with the wave-length as abscissas, is different and its maximum at a different point, than the intensity of the same radiation, plotted with the frequency as abscissas. The rational scale of any periodic quantity is the geometric scale, where equal intervals represent equal percentual increase or decrease; that is, the logarithmic scale. This was realized long before science existed: it is the scale used in music, with the octave; that is, log 2, as abscissas


RED
ORANGE
YELLOW
GREEN
BLUE
INDIGO
VIOLET
76
69.1
67.2
62.4
57.8
54.6
49.2
43.55
40.8
40.5
39
Li
Li
Na
Tl
In
lgλ =0.58
0.6
0.62
0.64
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
0.82
0.84
0.86
0.88
0.9
$g_{42}$
fis
f
e
dis
d
cis
$c_{42}$
$h_{41}$
b
a
gis
g
fis
$f_{41}$

In Fig. 2 the mercury spectrum is given in polar coördinates with the octave, or the ratio of wave-lengths 2 ÷ 1, represented by 360°. For illustration, the frequency denotations of acoustics are recorded in Figs. 1 and 2; that is, one half-tone represents 30°.

For comparison the spectrum lines of Li, Na, Tl, and In are also shown.

Of the spectrum lines of mercury of approximate wave lengths:

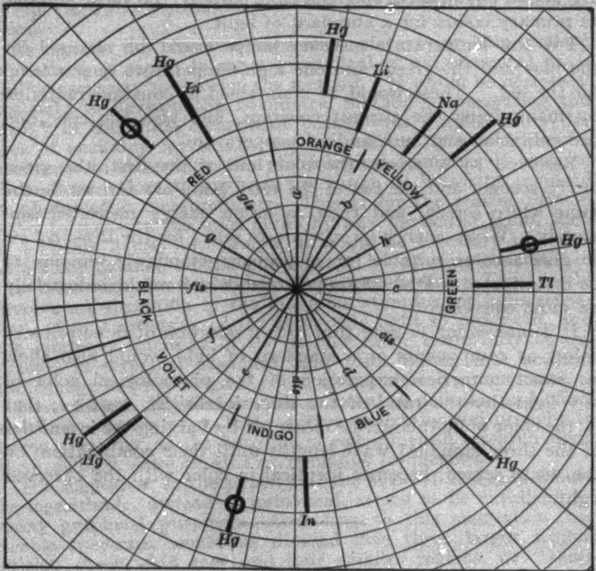

Hg
Hg
Li
Hg
Li
Na
Hg
ORANGE
YELLOW
RED
gis
a
b
h
g
Hg
fis
c
Tl
BLACK
GREEN
f
cis
VIOLET
e
dis
d
INDIGO
BLUE
Hg
Hg
Hg
Hg
In

FIG. 2

| | | | | | |
|---|---|---|---|---|---|
| 40.5; 40.8;<br>violet | 43.55;<br>blue | 49.2; 54.6;<br>green | 57.8;<br>yellow | 62.4;<br>orange | 67.2; 69.1;<br>red*, |

the lines:

| | |
|---|---|
| Blue | 43.55 |
| Green | 54.6 |
| Yellow | 57.8 |

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* The wave-lengths of these red lines require re-determination. Some of the other lines are twins.

are the most prominent. The three red lines, and many more red lines, appear only at higher temperature, as in the Heraeus quartz lamp.

The three spectrum lines of mercury:

| | |
|---|---|
| Blue | 43.55 |
| Green | 54.6 |
| Red | 69.1 |

are about equidistant and therefore appear the most suitable as primary colors for a standard of light.

Two low-temperature mercury lamps would be required for the blue and the green, and one high-temperature quartz lamp for the red. These would be maintained at constant radiation by maintaining the current constant, and also the condition of ventilation and surrounding temperature.

Resolved by a prism, the blue line of the first, the green of the second, and the red of the third lamp are thrown on the same white screen, and their radiation energy measured separately. What energy proportion to select for the three colors, to give a color suitable for a primary standard, remains to be investigated. Probably a yellowish-white would industrially be most convenient.

It is interesting to note that such a selection of three primary colors as components of a standard of light would also allow an exact numerical expression of the physiological color of any light, by the ratio of the three intensities, $a \div b \div c$; that is, the color of light could be measured by varying the intensities of the three standard wave-lengths until their combination, on the white screen, becomes identical in color with the observed light.

## DISCUSSION ON "PRIMARY STANDARD OF LIGHT." ATLANTIC CITY, N. J., JULY 2, 1908

**A. E. Kennelly** (by letter): The paper presents a certain fundamental physical proposition relating to a fundamental standard of luminous intensity, and also a practical proposal suggesting a means for carrying out the proposition. In so far as concerns the physical proposition, it seems to be unassailable, and to offer a theoretical solution for the problem of realizing a standard luminous intensity of definite physiological value, and definitely measured energy; that is, in ergs per steradian, or ergs per cubic centimeter from point to point of the luminous beam.

As regards the practical suggestion of carrying this method into effect, it seems to me a great deal of experimental work will be necessary to develop the method. It would be necessary not only to develop the bolometric method of measuring the energy in the three component beams with a satisfactory degree of accuracy for standard purposes, but it would also be necessary to determine the physiological stimulus of each of these three colors throughout the range of intensity required in photometric measurements. This is for the reason that in order to measure the light given by any particular lamp, such as a Hefner flame, for example, it would be necessary to arrive at a color balance on the photometer, by altering the ratio of the intensities in the three component beams. This would involve an alteration in the luminous stimulus, or light sensation, of unit intensity of the composite light so produced, and the luminous intensity of the Hefner flame could only be expressed in terms of standard light after taking into account the change in physiological effect of the altered components.

Nevertheless, Dr. Steinmetz's proposal is definite, and offers a definite chance of realizing a true determination of light in terms of energy, as the outcome of experimental research along three defined wave lengths or luminous frequencies.

The suggestion in the paper that the scale of abscissas should be logarithmic, instead of numerical, seems to be excellent for many graphical purposes. According to this suggestion, the visible spectrum would be divided into three larger regions (violet, green, and red) and four smaller regions, or "semi-tones," namely, indigo and blue, on one side of the green, and yellow and orange on the other. This would make an optical scale of approximately three tones and four semi-tones, or ten semi-tones altogether. The division of the spectrum would thus naturally fall into decimal subdivisions instead of into Angström units. Each first decimal place, or tenth root of 2, would correspond approximately to a semi-tone of color, while two such decimal divisions would correspond approximately to a tone of color.

**Edwin P. Hyde** (by letter): It would be very desirable indeed, both from theoretical and practical considerations, to be able to define our standard of light in terms of the C. G. S.

system of units, rather than have it without any known connection with other physical quantities. The suggestion of Dr. Steinmetz would seem to make possible such a definition. According to the suggestion we would define, not a standard of luminous intensity, but a standard of luminous flux; and we would measure the intensity of an unknown source by comparing the illumination produced by the flux from that source with the illumination produced by the standard flux. Since according to our present methods what we actually do is to compare illuminations and reason by means of known or assumed laws to the luminous intensities of the sources producing the illuminations, it is only necessary that we have a standard luminous flux, and not that we have a source of standard luminous intensity.

The principal difficulty to be overcome in realizing such a standard as Dr. Steinmetz suggests is in accomplishing with the requisite accuracy the absolute measurement of the small amount of energy contained in a single bright line in the visible spectrum. The determination of the proper proportions of energy in the three regions of the spectrum to give the required color, and the reproduction of these three colors in their proper proportions, could probably be accomplished with sufficient accuracy, but the determination of the energy of each region in absolute units would be a much more difficult undertaking. It would seem to me that a suggestive method of procedure might consist of: first, in obtaining as intense radiation as possible for the objective measurements, and then cutting down the intensity, if necessary, by sectored disks or other suitable means for the photometric measurements; and secondly, in measuring objectively the energy both of the component wave-lengths and of the combined flux—the former to give the proper proportions, and the latter to give the total luminous flux. By this method, slight errors in determining the proper proportions of the component parts would only enter as second order effects if the total flux is measured accurately; and the larger the total quantity of energy measured objectively the more accurately can the measurement be made when we are dealing with relatively small quantities of energy.

Although there would be numerous advantages in such a standard as Dr. Steinmetz proposes, if such a standard could be realized, there is one slight disadvantageous feature, which, however, is not serious. It has usually been customary to take the standard of white light as the standard also of spectral distribution in spectrophotometric measurements. This can only be done, of course, when the standard has either a continuous spectrum, or else a large number of bright lines well distributed in the visible region of the spectrum. The use for spectrophotometric measurements of such a standard as that proposed by Dr. Steinmetz would not seem feasible.

With the adoption of a common international unit of luminous intensity maintained arbitrarily by means of incandescent lamp secondary standards, such as has been proposed, the demand for a suitable primary standard of light is not as urgent as it has been heretofore; it is nevertheless just as important as ever, and the proposal of Dr. Steinmetz to define the standard in watts, with a prescribed spectral distribution, is very suggestive.

**W. S. Franklin** (by letter): The establishment of a reliable and reproducible light standard is of very great importance, and we naturally look to our Bureau of Standards to carry out such researches as may be necessary for its realization. I therefore move that the Bureau of Standards be requested by the Institute of Electrical Engineers to undertake such researches as may be necessary to determine the practicability of the light standard suggested by Dr. Steinmetz,[1] and, to develop such a primary standard of light, if it be found practicable.

In asking the Institute to place itself on record in this matter, I must say that, as it seems to me, Dr. Steinmetz's proposal cannot be a complete solution of the problem. Indeed, I do not believe the problem is capable of complete solution. Our present ideas of precision, and the theory of errors of observation as it stands at present, have been developed almost wholly in connection with extremely precise measurements, such as measurements in astronomy and geodesy, where the thing which is measured approximates very closely an actual "state of permanency," that is, where the thing which is measured actually exists as an unvarying physical condition. In attempting to establish a standard of light, however, it is important, as it seems to me, to understand that the present ideas of precision of measurement are in many cases inapplicable. Measurement in its most general aspects consists in bringing two things or systems into a kind of congruence, and all errors of observation originate in the incompleteness of this congruence test. In view of this general statement it is possible to distinguish two classes of errors of observation, namely, (a) errors which are due to erratic variations in the thing or system which is being measured, and (b) errors which are due to erratic variations in the measuring devices. The former being inherent in the thing which is measured, may be called intrinsic errors; and the latter, being outside of the thing which is measured, may be called extrinsic errors.

The probable error of a result, in so far as it depends upon extrinsic errors (irregularities in the measuring devices), is a measure of precision in the ordinary sense of that term, whereas the probable error of a result, in so far as it depends upon intrinsic errors (irregularities in the thing or system which is being measured), is a measure of the degree of indefiniteness of the thing which is measured.

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[1] PROCEEDINGS American Institute Electrical Engineers, March, 1908, p. 297.

It is generally possible to distinguish between extrinsic errors and intrinsic errors, and it is desirable to use the term probable error (as calculated from extrinsic errors) as a measure of precision, and to use the term probable departure for that part of the probable error, ordinarily so-called, which depends upon intrinsic errors.

In order to make these ideas perfectly clear, let us consider a particular case of measurement relating to erratically[2] varying conditions. For example, let us consider the repeated measurement of the current which is delivered by an electric railway power station. The successive measured values of the current differ greatly from each other, and one might proceed in the ordinary way in the determination of the "probable error" of the result. Suppose, however, that the ammeter is carefully studied by measuring with it a very carefully controlled current output which is kept as nearly constant as possible. In this way the systematic and erratic errors of the ammeter may be determined, and the probable error of an ammeter reading under these conditions would be a measure of the precision of the instrument. Let $a$ be the probable error of a single observation of the ammeter, so determined. Let $A$ be the probable error of a single reading of the ammeter as determined from the residuals of the observed values of the current output of the station. Then $A^2 - a^2$ is the probable departure of the current output of the station at any given instant from its mean value; that is to say, the difference between the mean value of the current output of the station and its actual value at any instant is as likely to be greater than $A^2 - a^2$ as it is to be less than $A^2 - a^2$.

Suppose the value of $a$ in the above discussion to be one ampere and the value of $A$ to be ten amperes. Then it is evident that the extrinsic errors (due to irregularities in the measuring device) in the above measurement are entirely negligible in their effect on the result as compared with the intrinsic errors (due to irregularities in the system which is being studied).

Ordinary photometry presents a case in which intrinsic errors are very great, because the actual intensity of light sensation depends upon so many varying conditions which are beyond control; in fact, the intensity of the light sensation which is produced by a given beam of light depends upon manifold individual peculiarities of the person, upon the degree of fatigue of the retina, and upon the degree to which the sensation is enhanced by attention, to say nothing of variations in composition of the light (relative intensities of the various wave-lengths which are present). It would therefore seem to be hopeless, and indeed meaningless, to attempt to establish a unit of light which would be completely definite except in so far as the physical character of the light is concerned. The proposal of Dr. Steinmetz does, in fact, seem to provide for complete definiteness of the light unit from a physical point of view, and the degree of precision with which this light unit might be reproduced would probably be so great as to leave nothing to be desired, considering the very great intrinsic errors in photometric measurements.

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[2] Any set of varying conditions must be thought of as erratic when no attempt is made to analyze the varying conditions into systematic groups. Thus the variation of current output of an electric railway power station is to be thought of as erratic unless an attempt is made to study the mean daily and hourly fluctuations of load. For the present purpose, the current output of such a station is assumed to be erratic.

**Carl Hering:** I have been very much interested in this paper by Dr. Steinmetz, and am very glad to see a suggestion in a practical form of a new unit of light, based on the power equivalent. It interests me personally, because I have for a number of years (since 1901 or 1902) recommended that our unit of light should be based on the power unit, that is, that the unit of light should be defined as the light produced by one erg per second converted entirely into light.* But I suggested no specific way in which that could be carried out practically other than to base it on one selected wave-length, or on a certain average wave-length, and I am therefore very much pleased to see that Dr. Steinmetz has offered this very interesting and apparently possible solution.

There is another reason why it is desirable to use the power unit in which to express our unit of light. We have at present three groups of units, the absolute (or electrical) units, the gravitational units, and the heat units. All of our units, except those of light, can be referred to one of these three. They have as connecting links the mechancial equivalent of heat, the acceleration of gravity, and the specific heat of water. Each of these three groups of units was originally started on an entirely independent basis, and the connecting links had to be derived afterwards by experiment. We have at present a unit of light which does not belong to any of these; it is based on an entirely new foundation, and it will be necessary to find by experiment the connecting links with these three groups of units. Dr. Steinmetz's suggestion is not to form such a new group, but to start by making the unit of light coincident with one of the existing groups, namely, the electrical or absolute units.

The term "unit of light", used throughout Dr. Steinmetz's paper, might be confused with the term "candle-power" by those who have not paid particular attention to the subject of light units. Of course, he does not mean candle-power, he means flux of light, as he stated in his abstract. There is evidently no possibility of an equivalent between watts and candle-power. The only equivalent can be between watts and flux of light. Flux of light is equal to candle-power multiplied by a solid angle, or to illumination multiplied by a surface.† We use the term

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* See Conversion Tables, Hering, p. 3; also p. 147.

† See Conversion Tables, Hering, p. 147.

"watts per candle-power"—but, of course, that is well known to be an irrational expression, although it has come into our nomenclature. We mean, of course, watts per spherical or hemispherical candle-power.

I call attention to an error in the diagram of the musical scale, in which the "a" to the left should be "e." I suggest that the English equivalents be added to this musical scale, as it will then be more easily understood by English readers; Dr. Steinmetz has apparently adopted the German nomenclature. Why does he reverse the conventional methods in the diagram by having the shorter wave-length to the left and the longer wave-length to the right, instead of the reverse, which is the universal method in musical practice; also in showing the spectrum, in which, I believe, it is conventional to show the red end to the left and the blue end to the right? There is an error in the text a little further on: one tone represents 60 deg., not 30 deg.

At the close of the paper, Dr. Steinmetz says that any color can be made up of these three. I am interested in knowing whether he is really quite sure of that, for the following reason: If we take three colored pigments and mix them together, we will get a certain color; now if we take some of that mixed pigment, and mix with it some white pigment, and then take some more and mix with it some black pigment, we will have, with the original mixture, three distinct colors. Each one of them will have the same relative quantities of the three original colored pigments in it, and yet it will in itself be an entirely different color from the other two. It might be said that they are shades of the same color. Now the question is, whether a parallel to this exists in the mixing of light rays. That is, is there in the mixing of light rays, something which corresponds to the admixture of white pigment or black pigment to a colored pigment?

Some years ago, when I was interested in this subject of the equivalent between power units and light units, I desired to know about what the magnitude of that unit would probably be; that is, what the conversion factor between light and power would be. I found some determinations made quite a number of years ago and after recalculating them to bring them to our present units, I found the figures to be 5.3 spherical candles per watt.* That figure might be termed the electrical equivalent of light. Hence, if the original tests were correct (I took them as I found them and am not responsible for their correctness), the figure will be about of that magnitude, which corresponds to 0.188 watt per spherical candle-power. If this figure be correct, that would be the ultimatum which we will ever be able to reach, as it would mean an efficiency of 100 per cent.

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* Mechanical Equivalent of Light, Hering, *Elec. World*, April 20, 1901, p. 631.

The unit which Dr. Steinmetz proposes naturally involves the solid angle when reduced to candle-power, and we therefore have the choice now in defining that unit, of selecting either the steradian (or absolute unit solid angle) or the sphere, as the solid angle to be included in that unit. Selecting the sphere eliminates the troublesome $4\pi$ from most of our calculations of light flux, which are made in spherical candles, and are not based on steradians.

**Clayton H. Sharp:** I would like to submit that when any member of this Institute is going to present to us a general solution of the electric circuit and the general solution of the perhaps equally difficult problem of the standard of light, he should at least give us a chance to catch our breath in between.

It looks to me as if this were, in a way, a general solution of this problem. The whole question of the standards of light, the history of the subject, shows how difficult the problem has been. For many years the flame standards were used, and were sufficiently good for the purpose. With the introduction of electric lamps, which were capable of more accurate measurement, a greater precision in photometry was at once demanded, and certain fundamental difficulties which exist in flame standards became known for the first time.

As a solution of the question of a more reliable standard of light, Violle came to the front with his propositions, namely, the use, as a standard, of the light emitted by a square centimeter of platinum at its point of solidification. This proposal, being on the face of it very attractive, was received and adopted at several electrical congresses, but it has never been found feasible to put it into practical operation, because a sufficiently accurate reproduction of this so-called " absolute " unit of light could not be carried out. Other propositions have been made of a similar nature, and the proposal to use energy measurements is not a new one. We find that Lummer made an extensive investigation of a standard of light which was defined in this way: "the standard light shall consist of the luminous radiation from a surface of platinum brought to such a temperature that the ratio of the radiation which it will transmit through a certain cell containing water to its total radiation per unit surface is as 1 to 10." Now, it should be theoretically possible to define a standard in this way. The great difficulty with such a definition, however, is that it involves the measurement of the ratio of the intensities of radiation, one of which, at least, is very low. Another difficulty with it is that it depends upon the radiating properties of a certain substance, namely, platinum. This latter difficulty might be obviated by using, instead of the platinum surface, a surface of a theoretical black body. However, the first difficulty would remain, and it seems to be of sufficient importance to preclude the possibility of establishing an accurate standard in this way.

The proposition which is made to us to-day appears to be the very first one which offers a chance of the establishment of a standard of light based on energy measurements, and independent of the properties of any substance whatever. Not only does it offer us a standard of light, but it gives us also the possibility of a standard for the measurement of colored light, since a variation of the proportions of the different colors used will produce a variation in the resultant tint. The latter feature may very well be one of considerable importance in view of the ever-increasing diversity in tints of the lights that we have actually to measure in the photometer room.

As Dr. Steinmetz has said, we have to deal here with a physiological effect, and not with a purely physical effect. Ordinarily, the physiological effect which we get from an incandescent lamp, or from most of our light sources, is an effect made up of the various wave-lengths of the spectrum; in other words, the spectra of our common light sources are continuous spectra, and have difference in color on account of a continuous difference in the ratio of the intensities of the various wave-lengths.

It is to my mind an open question, one which must be submitted to experimental determination, whether we shall get ultimately the same effect from the admixture of three monochromatic lights that we would get from a polychromatic source; whether it is not possible that minor differences in the sensibility of individual eyes to the different colors will not become much more apparent when we measure a polychromatic source against a source which is made up of three colors, than when we are measuring two polychromatic sources, one against the other. Will the physiological effect of three colors mixed together in all cases be the same as the physiological effect of all the colors mixed together, though in varying proportion?

In regard to the difficulties of the actual energy measurements which are involved in the realization of this solution of the standard of light, it seems to me, while they are very considerable, yet they are not necessarily insuperable, because it is not necessary, as I understand it, to deal with any extremely small quantities of energy. There is no reason why the sources which are used for the production of these three lines should not be sufficiently powerful so that there will be no small concentration of energy in each of the lines, and so that it will become physically possible to measure the radiation-intensity of each of these lines with a sufficient degree of accuracy for the purpose. I think there is no doubt that the method ought to be given a very thorough trial indeed, and I think also that the place where it ought to be tried and investigated is the Bureau of Standards, at Washington, where the answer to the question can be found, if it can be found anywhere.

I think there was some confusion in the statements of the last speaker in regard to the nomenclature of this matter. As

I understand it, Dr. Steinmetz's proposal looks to the production of a standard illumination on a given surface. Now, illumination is not the same thing as candle-power, though it can be referred to the theoretical point-source of light placed at a certain distance from the surface which is illuminated. Neither is illumination simply flux of light, but it is flux of light per unit area, or flux density, and consequently the proposition is to produce, really, a standard illumination on a surface, and if we wish to refer that to an imaginary point-source of light, which really does not exist in the experiment, we can say that illumination is produced by a source of one candle-power. However, the solid angle does not enter into the question directly, neither necessarily does the candle-power enter into the question directly, nor does the $4\pi$ come in. It is a question simply of producing a unit or standard illumination on a given surface, or unit flux density, or unit flux per unit area; for when we get right down to the fundamentals, it is flux we have to deal with in the case of light. The candle-power notion or concept is more or less fictitious and superfluous, though convenient for many purposes. For other purposes, the candle-power notion cannot enter in; we must come to the idea of luminous flux and base our computation of illumination on the idea of a luminous flux, as is quite evident when we consider any space illuminated by the so-called indirect method, where the ceiling is brightly illuminated, and, serving as a secondary source of light, illuminates other parts of the room. Evidently, there is no candle-power there, it is all a case of luminous flux from the ceiling falling on other surfaces of the room and illuminating them.

I think we are to be congratulated that this first, and certainly we hope the true, solution for the absolute definition of a standard of light, emanates from this country, and is presented for the first time to this Institute.

**C. A. Perkins:** It is not necessary for me to add my congratulations to Dr. Steinmetz for his valuable paper, but I wish to emphasize the fact that it is a step toward the solution of a problem which is impossible from its nature.

As Dr. Steinmetz has just explained, illumination is a physiological phenomenon and cannot be measured. It is impossible to say that a red light is as bright as a blue light. It is impossible to say that a Welsbach burner is so many times as bright as a Hefner lamp. The ratio depends on the eye of the observer, and also is a matter of personal estimate or judgment, and is not capable of measurement.

Yet the proposed standard simplifies the problem of comparing lights of different colors very materially, by reducing all the colors to three.

The next step will be to fix upon numbers which may represent the brightness of each of these primary sources (in candle-power per watt) based upon the average judgment of a large number of observers. The number thus determined will be more or less arbitrary but will represent in a fairly satisfactory way the average judgment and the normal eye. When the relative brightness of the primary sources has been fixed upon, the various secondary standards—Hefner, pentane or incandescent lamps—may be expressed definitely in terms of the primary standards, and the comparison of colored sources will be definite, though it cannot be absolute.

**John B. Taylor:** Dr. Steinmetz has several times told me that he had no proper musical training or appreciation, but in this paper he gives us a rainbow set to music, and leads me to hope that he has taken up a new subject, old as an art, but still having many unsolved physical and mathematical problems.

I wish to point out a few discrepancies as they appeal to me. In the first place, if we are going to replot the spectrum on a rational basis, why do we use wave-length at all? The essence of light, as well as of sound, is frequency, and not wave-length. Sodium light has a certain rate of vibration, while its wave-length is only incidental to the transmitting medium, having one value in air and other values in glass, water, etc. The same is true of sound. Pitch depends on frequency, while the wave-length of a sound of given pitch has different values in air, hydrogen, water, and wood. So it seems we should rightly lay out the spectrum on the basis of frequency instead of wave-length, frequency being really the essence of light and color.

I agree with Mr. Hering, that the English and American names of the musical tones would be more appropriate for this Institute. The German " cis's " and " fis's " are not so familiar to most of us as c-sharp and f-sharp, which in addition to the misprints and backward arrangement, have obscured, the optical and acoustical comparison. The use of frequencies, rather than wave-lengths, will naturally bring red on the familiar left end of the spectrum and the musical scale will read from left to right.

I do not see the arguments for a logarithmic scale in representing the spectrum. The musical system, both melodic and harmonic, is based entirely on the ratios of frequencies, and music as written is essentially a curve or curves with time as abscissas and logarithms of frequencies as ordinates. I have never yet been able to find that there is anything in the optical scale corresponding to this matter of ratios in the acoustical scale. It is true that certain combinations of colors will be harmonious while other combinations will not be pleasing. For example, it is generally agreed that pink and red do not go well together. Is it possible to take two different colors and say that these are not harmonious, on account of the ratio of their frequency? There is a definite period in music. In a well-recognized sense, after the interval of an octave, we go over the same ground again.

I hope Dr. Steinmetz can show more clearly some periodic property of the spectrum or something depending on ratios of frequencies to justify the logarithmic plot.

**Carl Hering:** Dr. Sharp says there is some confusion of terms in my remarks. I am confident that Dr. Steinmetz will agree with me that his proposed unit is not a unit of illumination, as Dr. Sharp says, but a unit of flux, which is equivalent to illumination multiplied by an area, or candle-power multiplied by a solid angle—either one gives the same result. I am quite familiar with the various units and measures of light and the relations between them, as I gave some attention to this question of equivalency between watts and light some years ago and I am sure there is no confusion in my mind

**E. B. Rosa:** I am interested in this proposition of Dr. Steinmetz, and should sincerely like to see it realized. It would be important to make a serious attempt to get a primary photometric standard in this way, which should be sufficiently satisfactory to be considered to solve the problem. It seems probable that it might be somewhat difficult to make the energy measurements with the required accuracy, and perhaps this will prove to be an insurmountable difficulty; and yet I have no doubt that if the attempt were made seriously, sufficient information and experience would result from the work to pay for the effort, even if it did not result entirely satisfactorily. It often happens that when a serious effort on a difficult problem is made and continued, a great many new things appear in the work that are of considerable value, by-products, so to speak, of the investigation. I think this field might be a very valuable and promising one to investigate thoroughly, with the hope, of course, that the problem of finding a primary photometric standard would be solved. At any rate, I think it would be proper to consider it very carefully.

I appreciate also the words of confidence in the Bureau of Standards that have been expressed. This investigation is clearly in the field of work of the Bureau of Standards, and the Director of the Bureau would be very glad, I have no doubt, to take up the work without any request from the Institute, as soon as practicable. Nevertheless a request made by the Institute would be very proper, and I would be glad to see that request made formally, because, as you will easily understand, the Bureau has so many fundamental problems on hand, more than it can at present undertake, that it needs support in its work; it needs the expression of confidence of this Institute, and the moral support of the engineering fraternity at large in its work. Such support will enable it to get the assistance and to develop the force that it needs in order to take up such problems, and therefore it can do more of that kind of fundamental work if interest is expressed in such a concrete way as is here proposed. I can easily see that such an investigation might last over a considerable period of time. We now have some problems on hand that have already extended over considerable periods of time, but in most cases they have been very profitable investigations to pursue; and entirely apart from the primary objects of the investigation, the results have been of considerable importance.

I wish again to express my interest in the suggestion of Dr. Steinmetz, and certainly consider it of value.

**Carl Hering:** I make the motion that the Board of Directors of this Institute be requested to refer to the Bureau of Standards the question of the establishment of a standard of light as proposed in this paper of Dr. Steinmetz. (The motion was unanimously carried.)

**H. S. Carhart:** I have only a few words to add to what has already been said. I suppose the reason why Dr. Steinmetz has chosen three distinct wave-lengths to enter into this combination for luminous intensity or luminous flux is the fact that there are three distinct primary color sensations. It would be desirable, first, to be assured that we get an average determination of the wave-lengths of these three primary colors, as applied to the eyes of different individuals, because there is individuality in this matter. Secondly, we should measure the relative energy in the three wave-lengths to produce any definite color, such as yellowish white. This task would be one of considerable difficulty. In that way we should be able to get the average energy of the primary colors required to reproduce a light of any given tint and intensity. It can readily be seen that such processes as these would necessarily require a good deal of time in order to realize them.

I think one of the speakers has been confused a little, if I may call attention to the fact—the mixture of three colored lights is a totally different thing from the mixture of pigments. The mixture of pigments is a process of absorption, and the mixture of lights is a matter of superposition and addition. If we have red glass, which cuts off the violet end of the spectrum, and blue glass, which cuts off the red end of the spectrum, and if we put one in front of the other, the only light that comes through is a little of the red. This is like the mixture of pigments. We should be very careful not to confuse mixture of pigments with mixture of colors. What we have in the paper is three colored lights, coming from three sources of definite wave-length. I am greatly interested in the proposition, and think it is really hopeful enough to suggest to the Bureau of Standards, as has already been done, for investigation.

**Chas. P. Steinmetz:** Three colors I selected as primary colors, since three primary colors are sufficient by their combination to produce all other colors, representing these by the ratio of the energies of the three primary colors. As seen, this is essentially the representation of the points of the color plane by a system of symmetrical coördinates. Combinations of two colors are not sufficient to produce all other colors, but at least three are needed. In regard to the selection of the three primary colors, I tried to get three colors forming as nearly as possible an equilateral triangle in the polar diagram, or in the color plane, as shown, so as to get the maximum accuracy in their combination. There was a second consideration. The three points of the equilateral triangle I tried to select so as to have a maximum distance from the ends of the spectrum, since at the ends of the spectrum the physiological equivalent of power is low and vanishing, and therefore if one of the lines were chosen close to the end, as for instance dark red, it would mean there would always be a large percentage, in power, of red rays, even to produce a color which appeared to the eye deficient in red. For greatest accuracy, it is however desirable to have the three numerical values of power of primary colors as nearly of the same magnitude as possible. The two outside colors, blue and red, are therefore chosen about equidistant from the ends of the spectrum, as two corners of the equilateral triangle, which brings the third corner into the middle of the spectrum, in the green. You can choose any other set of spectrum colors, but I believe the best way would be to choose the three points of an approximately equilateral triangle, with the two outside corners as far away from the ends of the spectrum as possible, as was done by me.

As regards the scale adopted, I must apologize, for my musical education was so badly neglected that I still used the Italian scale, instead of the flats and sharps of the English notation. I believe, however, it will be equally intelligible.

As regards the wave-length; what I give is not really the logarithm of the wave-length, but the logarithm of the frequency. The wave-length of light is not constant, but a function of the medium. However, the logarithm of the wave-length in any medium is the same, and is also the logarithm of the frequency, except with reversed sign and shifted decimal point. It therefore is immaterial, in the logarithmic scale, whether wave-length or frequency is used; either gives the same curve or figure, except turned over, and it obviously is immaterial whether the red end of the spectrum is on the right or on the left side.

In regard to the bearing of the acoustic scale, you will see if you look at the polar diagram, that it is material, and that the wave-length is not the right measure. In the acoustic or polar diagram, two diametrically opposite points are of complementary color, that is, combined give white light, or approximately white light (after all " white " is a rather indefinite expression). This is not the case in the representation by wave-length, nor in the representation by frequency; but in either case you find that one-half of the visible spectrum represents much less variation of the physiological effect, that is, change of color, than the other half.

About color representation: If we represent colors by a combination of the three primary radiations, we still have different values for the same color, representing different color densities. For instance, a certain yellow light may be represented by: red, 50; green, 50; blue, 0. The same yellow light, but of a lighter shade, may be represented by: red, 45; green, 45; blue, 10. Still a lighter shade by: red, 40; green, 40; blue, 20; until ultimately you reach white light.

I believe that even the densest yellow light, produced from the primary colors: red, 50; green, 50; blue, 0, is yet not the spectrum yellow; that is, not as pure yellow as the spectrum yellow, and that the spectrum yellow would be represented by something like: red, 55; green, 55; blue, $-10$. This ratio: $55 \div 55 \div -10$ represents a point of the plane outside of the equilateral triangle formed by the primary-color points, and such probably is the case with the spectrum yellow and with all the spectrum colors, except the three colors selected as primaries.

Physically, this means that if we desire to compare the spectrum yellow with our three-color combination, no combination of red, green and blue can be found to equal the spectrum yellow, but that a combination of red and green can be found to equal a combination of the spectrum yellow and blue, and in this case the blue becomes subtractive. It is the same as balancing a weight by putting too much weight on the other scale, and then putting some weights on the first scale, *i.e.*, balancing by taking some weights back. We may do the same in color representation. Theoretically, I believe all pure spectrum colors, except the three selected as primary, would be represented by combinations of the three primary colors with one of the primary radiations as negative.

As regards the mechanical equivalent of light, I do not agree with the value mentioned by Mr. Hering, 0.188 watts per candle-power, for the reason that efficiencies of arcs have been measured which give lower watts per mean spherical candle-power than that. In some powerful titanium arcs values considerably lower have been found, and in those cases the efficiency was still far below 100 per cent. Estimating the loss of power by invisible ultra-red and ultra-violet radiation, by heat conduction, heat convection, air currents, etc., the efficiency was undoubtedly below 50 per cent., probably nearer 10 per cent. I believe the approximate equivalent of white light is probably something more nearly fifty candle-power per watt—that is, 0.02 watts per spherical candle-power. I make no claim to this value, but it is merely an estimate based on my experience—it may be more or less, but I would expect the equivalent of white light to be approximately 50 candle-power per watt, or thereabouts. For other colors of light there would be different values. Probably in the case of the green light, the candle-power per watt would be much greater, in red light or blue light much less. It is a function of the color.

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# AN IMPERFECTION IN THE USUAL STATEMENT OF THE FUNDAMENTAL LAW OF ELECTROMAGNETIC INDUCTION†

BY CARL HERING

The fundamental law of electromagnetic induction, which is the basis of all our present mechanical generators of electric currents, is, in general, stated in two different ways. Faraday's statement is to the effect that if a conductor cuts magnetic lines of force, an electromotive force is generated. This simple statement, however, has been changed by later authorities, who define the same law by saying in effect that when the amount of flux enclosed by an electric circuit is changed, an electromotive force is induced. This is the more usual form taught to-day and recopied in most text-books in preference to Faraday's statement of it.

Maxwell in his classic treatise, Sec. 531, Vol. II, states the law in these words:

> The whole of these phenomena may be summed up in one law. When the number of lines of magnetic induction which pass through the secondary circuit* in the positive direction is altered, an electromotive

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†The object of this note is to point out that the usual and well-known statement of the fundamental law of the induction of currents by magnetic flux, is not correct as a universal law, and requires to be modified; when, applied as it is usually stated, it sometimes gives entirely erroneous results, although it is correct under the usual conditions. An essential qualification has apparently been overlooked. The proof is given by a simple experiment. The possibility of linking or unlinking an uninterrupted electric circuit with a magnetic circuit, without producing any induction, is shown. It leads to a clearer conception of induction and to a new form of continuous current generator.

* He had just previously shown that a magnet and a primary circuit are here equivalent.

> force acts round the circuit, which is measured by the rate of decrease of the magnetic induction through the circuit.

Another high authority, Professor J. J. Thomson, in his excellent and more modern treatise (Elements of Electricity and Magnetism, Sec. 229, p. 388) states the law in these words:

> Whenever the number of tubes of magnetic induction passing through a circuit is changing, there is an e.m.f. acting round the circuit equal to the rate of diminution in the number of tubes of magnetic induction which pass through the circuit.

Other writers merely used different expressions to the same effect. One well-known form of expressing this law, is to consider the magnetic circuit and the electric circuit to be like two links of a chain: then, during the process of linking them together, an electromotive force is induced in one direction; when unlinking them, an exactly equal electromotive force is induced in the other direction.

The well known natural consequence of this law, when stated as it usually is, is that the same flux cannot be linked and unlinked repeatedly by the same closed circuit without generating alternating electromotive forces, hence the commutator of direct-current machines, and the inoperativeness of many suggested unipolar machines. Although not stated directly it is presumably understood that the electric circuit is not opened; the magnetic circuit unfortunately cannot be opened as there is no good magnetic insulator known.

Innumerable methods have been suggested, and doubtless many have been actually tried, to obviate, overcome, or neutralize this reverse electromotive force so as to produce direct currents without the necessity of commutation, but they have all failed except the Faraday unipolar dynamo, which has apparently not come into use for the usual voltages. According to this law, as it is usually stated, the former have failed because of this reverse electromotive force. It is now believed to be generally accepted and taught that this law is universal, and the attempts to evade it have lessened.

Recent investigations made by the writer and followed by experimental demonstrations, have, however, shown that the usual statement of this important law is imperfect, and that it requires to be modified in order to become universal. Probably others besides the writer have been misled by accepting this law as usually stated to be correct and universal. It will be shown below that it is quite simple to produce linkages or unlinkages, or to change or reverse the same flux enclosed by the same continuously closed circuit, without producing any electromotive forces whatsoever. It is true that the law as usually stated, seems to apply correctly to all the usual methods of producing electromagnetic induction at the present time; but it will be shown that, taken literally as usually stated, it is quite incorrect under certain other conditions, giving entirely erroneous results and must therefore be modified in order to become universal, or else be limited to those conditions to which it does apply, in which case it cannot of course be called universal.

It is not denied here that Maxwell himself may have elsewhere described these limiting conditions, or may have elsewhere described induction under those unusual conditions. If so, his followers should have made similar explanations in teaching his version of the law, so that students should not be misled.

Some time ago the writer suggested a so-called unipolar machine (that is, one having unipolar instead of bipolar induction) based on an apparently new phenomenon,* which would be operative if this law, as it is usually defined, is correct; but it was thought by him and also by Dr. E. F. Northrup, that it would fail, notwithstanding this law. It was concluded that it was not the change of flux in a circuit, or the linkages of the *circuit* with the flux, which determined the induction, but that it was essential that the *material* itself which composed the conductor must actually cut or move through the flux, (or the flux move across it). It was thought that Faraday's way of stating the law was nearer correct than the supposedly improved and more general form of his successors.

The following simple experiment was devised by the writer to investigate the correctness of these conclusions.

A loop $L$, Fig. 1, was formed of two flexible strips whose ends pressed together at the joint $J$, and the circuit of the loop was closed through a galvanometer $G$. On moving this loop over one leg of a U-shaped permanent magnet $N S$ from the dotted position to that shown in full, an electromotive force was induced, as is well understood. The magnetic flux has thereby been linked with the electric circuit; the flux enclosed by the circuit has been increased from zero to the maximum; or to use Faraday's terms, the lines of force in the air from one pole to the other, have been cut by the conductor. So far, the law as it is stated is correct.

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* "A Practical Limitation of Resistance Furnaces; the 'Pinch' Phenomenon." By Carl Hering. Trans. Amer. Electrochemical Soc., Vol. XI, 1907, p. 329. Also "Some Newly Observed Manifestations of Forces in the Interior of an Electric Conductor". By Edwin F. Northrup. Physical Rev., Vol. XXIV, No. 6, June 1907, p. 474.

If this loop be now moved as shown in Fig. 2 from the dotted position to the one shown in full, by passing the leg of the magnet through the joint $J$ of the loop, but *without opening the circuit*, the flux and the circuit will be unlinked again; that is, the flux enclosed by the circuit will again be reduced from a maximum to zero, and the circuit will have cut the same lines of force in the opposite direction, as it is well known that all the flux of this magnet passes through its interior.

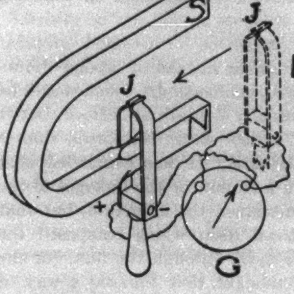

Fig.1

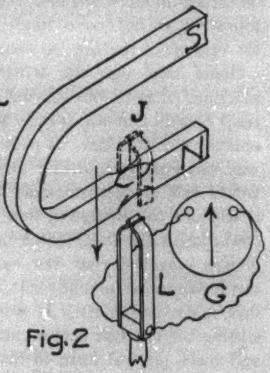

Fig.2

According to the law of induction as quoted above from Maxwell, or J. J. Thomson, and as almost universally accepted, there ought then to be an electromotive force induced which is opposite and exactly equal to that induced by the first movement shown in Fig. 1, which will be seen by reading the law as there stated, on to this experiment. The fact is, however, quite the contrary; *there is absolutely no electromotive force induced by this unlinking*. Moreover, the same circuit is then free from flux and can be linked again repeatedly in the same direction with the same flux as before; a rapid repetition of these two movements increased the deflection more than ten fold.

This is believed to be the first direct and simple experiment which proves conclusively that it is possible to link and unlink a flux with a closed electric circuit without any induction, thereby showing that the usual statement of Maxwell's version of the law should either be restricted to certain conditions, or be modified so as to become universal without the necessity of more or less complicated interpretations.

It is also believed to be the first experiment which shows that in applying Faraday's version of the law it is important to make a distinction, heretofore apparently not recognized, between the conductor itself and the mere current path or circuit, when induction is concerned.

Through the kindness of the Leeds & Northrup Co., the experiments were made in their well equipped laboratory and were confirmed by my friend, Dr. Northrup himself. With his usual care and precision he even amalgamated the contact at the joint *J* and at the surface of the steel magnet where the loop passes over it, so as to be absolutely sure that the total absence of a deflection was not due to a possible open circuit. The magnet was ground down to a knife edge on each side, forming a lozenge shaped cross-section at the place where the passage of the strips over the magnet took place.

To be still further assured that there was no open circuit during this unlinking, the writer modified the test by passing a constant current from a battery, through the circuit during both the linking in Fig. 1 and the unlinking in Fig. 2. The linking was then found to increase (or diminish) the deflection, but during the unlinking the deflection remained constant; had the circuit been opened during the unlinking, the deflection would have indicated it at once by falling as was shown by unlinking the loop over part of the magnet which had been painted. The galvanometer used was one that was suitably adopted for the necessarily low electromotive force and low resistance; its sensibility was 38 megohms, and its resistance was 140 ohms; the deflections were therefore very decided and reliable; the test was repeated numerous times, thus leaving no doubt as to the correctness of the results.

This experiment, therefore, teaches us that it is *not* the linking and unlinking of the magnetic and the closed electric circuits, and it is *not* the changing of the amount of flux enclosed in the closed circuit, which is the prime cause of the induction, as it proves that such unlinking or changing of the flux can take place *without* any induction whatsoever. The cause of the induction must therefore reside elsewhere.

It appears from this experiment that it is the *material of the conductor of the current*, and not merely the circuit itself, which must actually move across the flux (or the flux move across it) in order to cause induction. In the experiment, the circuit itself did move across the flux during the operation of unlinking because the unlinking of the two circuits was effected completely; both circuits having remained unbroken, it of course follows that they must necessarily have cut each other. The only part of the conductor which did not move relatively to the flux during the unlinking, is that part of the material composing the magnet which is embraced between the two contacts; the circuit here did cut through the flux, but the material of the moving conductor did not; this appears to be the only difference, hence it seems essential that this feature should now be embodied in the statement of a law which is intended to be universal.

As the term "conductor" implies the material thing itself, when distinguished from a theoretical line representing the closed circuit or current path, it might suffice to emphasize the condition that the conductor itself must cut across the flux, in stating the law in Faraday's way.

If that later statement of the law which is in terms of the change of flux included in a circuit, is still to be used as a universal law, some limiting clause will now have to be added to cover the case shown in this experiment. A "change of flux" is not sufficiently definite, the change must occur in a certain way in order to be effective. But in view of the fact that this experiment seems to show that the real or prime cause of the induction does not reside in the "change of flux" at all as is usually believed it would seem to the writer to be preferable not to continue to define induction in those terms at all, but to use other terms which more clearly embody what seems to be the real prime cause. In other words, it seems to the writer to be better now to go back to Faraday's original definition in terms of cutting the magnetic lines of force, than to use the one of Maxwell which is in terms of the change of flux.

Maxwell and his followers, in generalizing this law, seem to have gone too far, because, *as it is quoted above*, it includes in its scope a case in which it gives entirely erroneous results. His predecessor, Faraday, was nearer correct when he described the induction to be due to "cutting the lines of force." Even Faraday's definition as incorrectly interpreted by others who used the word "circuit" instead of "conductor" (Faraday apparently did not do so himself), should now be modified or qualified to the effect that the conductor itself, and not merely the circuit must do the actual cutting.

As to stating the law in terms of the linking and unlinking of the two closed circuits, it seems difficult to so qualify it now as to limit it to the specific and probably the only kind of linking and unlinking which *is* effective, and exclude the kinds which are ineffective. This is unfortunate as this idea of linkages formerly afforded a very convenient and useful conception of the nature of induction.

In Faraday's original experiment with a revolving bar magnet and a loop running from one pole to the middle of the magnet, this same phenomenon occurs. The *circuit* itself cuts the flux in the interior of his bar magnet, as Faraday himself says; but he did not notice that the corresponding part of the conductor itself, does not; if it had, he would not have obtained the results described. He thought the lines of force remained stationary in space while the magnet revolved. The important distinction between the material of the conductor, and the circuit itself, when induction takes place, seems therefore to have been overlooked by him, notwithstanding that in stating the law he used the term conductor and not circuit.

The writer desires to repeat that the usual statements of this law in terms of the change of flux seem to apply correctly to all the ordinary cases occurring in our present practice, and that the limitation now pointed out therefore does not alter in anyway the former applications of that law to those cases. But as those statements of the law are directly contradicted by the present unusual case, the law as usually stated is not universal; and it misleads as it did the author, by making it appear that certain actions will always take place, when as a fact they sometimes do not. These statements of the law are unsatisfactory also in that they intimate that the *prime cause* of the induction resides in the changing of the flux embraced by a circuit, when it seems now as though it resides in the actual passage of the flux across the material conductor itself, and that it is located there and is not a property of the circuit as a whole.

It may be claimed that this experiment does not show an "error" in the usual statement of the law, and that it might equally well be claimed that Ohm's law is in error because counter electromotive forces, inductances, capacities, skin effects, Hall effects, etc., in the circuit, modify the results obtained by it.

But the latter does not seem to be a parallel case; Ohm's law treats of the relations of three quantities, and if there are more than three, the excess must either be eliminated or expressed in terms of one or more of the three, before Ohm's law can apply as such, and it is then correctly stated. The law of induction, however, as usually stated, actually gives totally erroneous results in some cases, as will be seen by reading Maxwell's or J. J. Thomson's statement of the law, on this experiment. This law treats of three things (1) a circuit, (2) an alteration of the magnetic flux enclosed by it, and (3) an electromotive force produced by such an alteration; it treats of nothing else; and if the results specified by this law *as usually stated* are not obtained or are not correct, when no additional quantities are introduced it seems to the writer to be justifiable to say that the statement of the law is faulty and is actually in error when applied to those cases. Aside from this, this law seems to give an erroneous conception of the real cause of the phenomenon.

The present experiment is also thought to be of considerable interest in connection with the long discussion of many years duration, as to which of the two so-called theories was the better one to teach and use, the one of Faraday based on the "cutting of lines of force," or the one of Maxwell based on the "change of flux enclosed by a circuit." It seems to show that after all, Faraday's original statement which was based on experiment, was more universal than Maxwell's, which latter appears to have been a mathematical generalization.

Another feature of interest of this experiment is that it seems to indicate that the induction is localized, and takes place only in that part of the conductor which passes through the flux, and not in any other.*

There seems to be no reason why the present experiment should not give the same results if a piece of copper were introduced in or around that part of the magnet over which the loop slides; and that this piece of copper might be insulated from the magnet, in which case the loop may have more than one turn, if there are a corresponding number of insulated copper pieces. This was not tried.

Fig. 3 was suggested by Dr. Northrup to show how the experiment might be repeated without involving any iron or steel in the phenomenon. Two solenoids are used instead of the permanent magnet, and one of them is surrounded by a copper ring *C* over which the joint of the loop passes.

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*The so-called "Dead Wire on Gramme Armatures." By Carl Hering. The Electrician and Electrical Engineer. May, 1887, p. 171.

A continuous current generator without a commutator may be constructed in accordance with the results taught us by this experiment. Fig. 4 shows diagrammatically a simple way in which this might be done for demonstration purposes, although not for a commercial machine. The diagram explains itself; a number of magnets are placed symmetrically around a center and a single circuit of as many loops as desired may be made to cut all of the fields in such a way as shown, that the electromotive forces induced in the several loops are added in series. Doubtless the machine would operate as a motor also. Unfortunately, however, such a machine seems to have the same limitations as the usual unipolar ones, in that two sliding contacts moving at high speed, are required for each element of the circuit which passes through the flux.

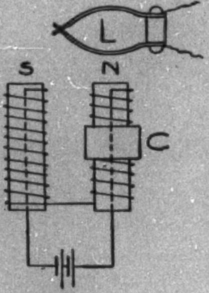

Fig. 3.

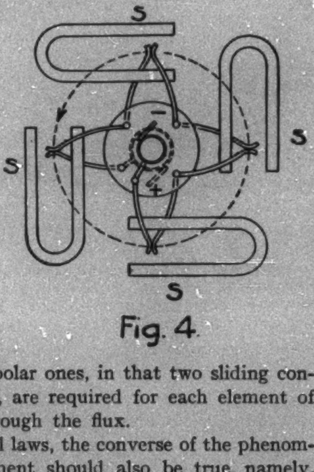

Fig. 4

In accordance with general laws, the converse of the phenomenon shown by this experiment should also be true, namely, that when applied to motors it is the material of the conductor itself, and not merely the current or the circuit, which is caused to move through the magnetic field; in other words the electromagnetic forces act on the conductor and not on the circuit or on the current.

In this form it has long been known. For instance in a Faraday disc unipolar machine when used as a motor, it is not the circuit nor the current which is rotated through the disc, but it is the disc itself, on which the forces act. In other words, it is not necessary to make the disc of separate radial wires insulated from each other, in order to confine the currents to radial paths. On the other hand, however, there is the Hall effect in which it is the circuit, that is, the path of the current, which is deflected in a large conductor, when the conductor is not permitted to move.

The phenomenon illustrated by the present experiment may perhaps explain the reasons for the well known action of a magnet in "blowing out" an arc. The magnet appears to exert its forces on the material forming the conductor, namely on the ionized conducting gases which carry the current, and not on the current itself; the current follows the moving conductor, instead of the conductor following the moving current path.

The present experiment naturally gives rise again to the interesting question of what forces exist, if any, which oppose the change of the path or circuit of a current which is flowing through a large moving conductor. If for instance, a current is passed from one side of a rapidly running river to the other through the water, is the path different from what it would be if the water were at rest? A study of this question may not lead to any practical results, but it may nevertheless be of interest and perhaps be instructive in aiding us to obtain a better conception of the true nature of conduction.

I desire to repeat here that the error pointed out by this note does not affect the applications of this law to the usual electromagnetic machinery and apparatus of the present, and is therefore of no importance in that sense; the importance of it lies in showing that the law as usually stated, and when applied directly as stated, gives entirely incorrect results under certain conditions differing from the general ones; also that it misleads; and that it is not universal; to become universal it should be modified instead of having to resort to what is little short of mathematical juggling to make it fit this case. The importance of this experiment is perhaps, that it seems to give us a clearer conception of the real phenomenon of electromagnetic induction, its probable cause and its location; it shows conclusively that the change of flux enclosed in a circuit cannot by itself be the prime cause of induction; unless a further essential condition be fulfilled, such a change of flux fails to induce an electromotive force.

Attention might here be called to a very early experiment of

Faraday published in 1831, which has apparently been overlooked by the followers of Maxwell; it is described in his Researches, Paragraph 101. Maxwell's statement of the law also fails to apply to this, unless modified, as the flux included in the circuit always remains the same even though there is an electromotive force induced in that circuit. It also requires some interpreting of the law to make it apply to the case of the Faraday unipolar machine, a fact which many students and their teachers have experienced.

The writer desires it to be clearly understood that he does not deny that the usual statement of the law involving the change of flux idea, might be made to cover this experiment by adding various conditions or restrictions, or by various more or less complicated interpretations now suggested by the results of the experiment itself, and it might be claimed that there is then no error in it as a universal law. The writer's comments were intended to apply not to such modifications or interpretations of that law, but to the law as it was published and republished, and as it is and has been taught to students. In that form a student would certainly not have predicted the results of this experiment correctly by it, for in that form it directly contradicts the results. Faraday's statement of the law, on the other hand, when stress is laid on the distinction between the conductor and the mere circuit, predicts the correct result directly and without interpretations or other conditions. But aside from the question of whether or not it can be called an actual error, the more important question is now, whether Faraday's version is not simpler, more universal, safer, more direct, and much easier for students to learn and comprehend than Maxwell's.

## DISCUSSION ON "AN IMPERFECTION IN THE USUAL STATEMENTS OF THE FUNDAMENTAL LAW OF ELECTROMAGNETIC INDUCTION." ATLANTIC CITY, N. J., JULY 2, 1908

**Chas. P. Steinmetz** (by letter): Mr. Hering's paper is interesting in that it draws attention to a looseness in the form of expressing this law, which is frequently the cause of serious misunderstanding, and the waste of much energy and time. For instance, in the attempts to invent a coil-wound unipolar machine much useless effort could have been avoided by a clearer distinction between the general law and the special case of its application to a continuous closed conductor. While Mr. Hering's experiment is interesting in showing an instance of a closed electric circuit in which the number of interlinkages with the lines of force changes without inducing an electromotive force, it is not startling to me, as the reverse case, the electromagnetic induction of an electromotive force, in a closed circuit, without any change of the number of interlinkages of the circuit with the magnetic flux, is illustrated by practically every unipolar machine. There are thousands of kilowatts of such machines now in commercial operation.

The general law of electromagnetic induction is:

> In a conductor moving relatively to a magnetic field, an electromotive force is induced which is proportional—and in absolute units equal—to the product of the intensity of the magnetic field, and the components of the length, and of the velocity of the conductor at right angles to the magnetic field and to each other.
>
> If an electric conductor moves relatively to a magnetic field, an electromotive force is induced in the conductor, which is proportional to the intensity of the magnetic field, to the length of the conductor, and to the speed of its motion perpendicular to the magnetic field and the direction of the conductor.

Using the pictorial representation of the magnetic field by the lines of magnetic force, as given by Faraday, this means, that the electromotive force induced in the conductor equals the rate of cutting of the conductor through the lines of magnetic force, that is, gives: $e=\frac{d\,\phi}{d\,t}\,10^{-8}$ volts, where $d\,\phi$ are the lines of force cut by the conductor during the time $d\,t$.

Applying this general induction law to the special case—which is the most important, but not the only case met in electrical engineering—of a continuous conductor closed upon itself, or a turn, it follows, as conclusion, that the total electromotive force or resultant electromotive force induced in the turn equals the rate of change of the total number of magnetic interlinkages of lines of magnetic force enclosed by the turn, hence is: $e = \frac{d\,\phi}{d\,t}\,10^{-8}$, where $\phi$ is the number of lines of magnetic force enclosed by the turn or, leaving Faraday's pictorial representation, $\phi$ is the magnetic flux enclosed by the turn.

Maxwell and J. J. Thomson's statement, as quoted by Mr. Hering, are not the most general expressions of the law of induction, but its formulation for the special case discussed by these scientists, of a turn moving with regard to the magnetic field.

Mathematically speaking, we may see that Maxwell's law is the integral expression derived from the general or differential law by integration over the whole circuit, under the "terminal" or "limit" conditions of continuity of conductor and continuity of motion, and does not apply to Mr. Hering's experiment, or to the general design of unipolar machines, which do not fulfil the conditions of continuity of motion, but have parts of the conductor sliding over other parts.

Faraday's expression, of cutting of lines of magnetic force by the conductor, is the general law; but in its application to unusual cases it must be kept in mind that the "line of magnetic force" is merely a pictorial representation of the magnetic field in space, as characterized by the two constants, intensity, and direction. This pictorial representation, when carried so far as to apply to its physical existence, may lead to wrong conclusions; for instance, when discussing whether the lines of magnetic force of a revolving magnet move with the magnet or stand still. Assuming, for instance, a bar magnet of circular section $x^2+y^2=r^2$, revolving around its axis $z$. Then in any point in space, outside of the magnet as well as inside, the intensity as well as the direction of the magnetic field is constant; that is, the magnetic field is constant, or stationary in space, regardless of whether the magnet stands still or revolves. Assuming a second system of coördinates with the same axis, $z$, as the magnet, and with the other two axes, $x_1$, and $y_1$, stationary with regard to the magnet, and revolving in space with the revolutions of the magnet, then with this coördinate system, $x_1$, $y_1$, $z$, the magnetic field at any point, inside of the magnet as well as outside, is also constant in intensity and in direction; that is, is stationary. Or in other words, while the two coördinate systems $x$, $y$, $z$, and $x_1$, $y$ , $z_1$, revolve with regard to each other, the magnetic field of the magnet is constant in intensity and in direction, that is, it is stationary, with regard to either. Physically, this is nothing exceptional; it merely means that the condition of stress, which we call magnetic field, is unvarying in its distribution in space as well as with regard to the revolving magnet. Picturing to ourselves the magnetic field as lines of magnetic force, it would mean that the lines of force are at the same time stationary in space and also revolving with the magnet. This suggests that all pictorial representations, no matter how useful, may occasionally become ambiguous. In such cases the only safe way is to go back to the entities proper, in the present case, the magnetic field as a quantity characterized by intensity and direction.

Unfortunately, in teaching, instead of the general law of induction, there is frequently given to the student, its specific application to the turn or closed continuous conductor as more convenient to illustrate and to understand. While in the introduction to the elements to electrical engineering this is permissible, to get a complete understanding of the phenomena of induction, it must be supplemented by an exact discussion of the general induction law, that is, the mathematical formulation of Faraday's pictorial representation.

**A. E. Kennelly** (by letter): The experiment described in the paper is both interesting and instructive. Although the experiment illustrates the proper application of the law of induction when applied to electric circuits, it does not in my opinion controvert the existing law when properly interpreted; that is, when interpreted as intended to be expressed by its founders, Faraday, Maxwell, and others.

When it is stated that the electromotive force round a circuit is equal to the time-rate of change of the flux linked with that circuit, it is inherently assumed that the circuit is not interrupted and then established around a new boundary. It means, as I understand it, that the circuit contains a simply connected region of magnetic flux, through which the boundaries may be flexibly caused to wander at will. Maxwell specifically rules out the case of multiple-connected regions, by a special proposition to that effect. In Mr. Hering's experiment, the boundary of the circuit is cut at one point, and simultaneously a second circuit embracing flux is introduced at the gap, in such a manner that by sliding along the boundaries of the second circuit, the magnetic flux may be caused to disappear from the embrace of the first circuit without any intersection of flux by the edge of that circuit. This, to my mind, is juggling with terms, just as though the circuit were cut and then reclosed through a quiescent loop linked with a magnet. Manifestly, no current would be induced through the galvanometer by reason of that change, although in one sense of the word "circuit", all of the flux in the loop has suddenly been introduced into the circuit.

The instructive value of the experiment described in the paper lies, to my mind, in clearing up the question as to which is the primordial proposition; that electromotive force is induced (1) by the movement of magnetic flux across the boundary, or (2) by the introduction of flux into a loop or circuit. As ordinarily stated, the two propositions are as closely connected as the propositions concerning the priority of the chicken and the egg, because flux cannot cut the boundary of a loop at any point without altering the flux contents of the loop, nor can the flux in a loop alter without cutting the boundary somewhere. The experiment shows, however, that where flux comes into a field from a balloon, as distinct from walking over a fence, no electromotive force is induced, and this indicates that the cutting is the primordial conception, to which enclosing is secondary. Of course this cutting electromotive force occurs as much in insulators as conductors, but can ordinarily be revealed only through the use of conductors. When, therefore, a closed circular solenoid, or anchor-ring, is wound with a primary and with a secondary coil, we know that in the steady state, if the solenoid is properly wound, there will be no external magnetic flux due to current in either winding; but the change of internal flux due to change of current in one winding induces electromotive force in the other, as in the ordinary transformer. At first sight, this would look as though there were change of enclosing flux without any cutting, but in the light of this experiment it seems clear that this is not the case. There must be cutting of flux passing from outside to inside of the secondary coil, but, incidentally, all the external flux cancels off, or becomes zero in the final steady state.

Summing up, then, I should think that this experiment shows that when the ordinary proposition is enunciated concerning induction of electromotive force with change of flux enclosed in a circuit, it should be borne in mind that the circuit is not to be juggled with by interrupting it and changing it from a simply-connected to a multiple-connected space. It must consist of a single, continuous boundary which, if it moves, moves continuously through simply connected space. In this understanding, I think we shall all agree.

**Elihu Thomson** (by letter): I agree with Dr. Kennelly in his view of the state of the case. By passing the spring clip over the magnet leg the circuit is virtually opened so far as magnetic induction is concerned, and an immovable section of conductor is substituted in the gap where all the flux to be cut then exists. The conclusion that the real physical substance of the circuit (the matter of the circuit) must cut or be cut by the lines is in accordance with my view of the subject. There are innumerable phenomena which have confirmed that idea of what is really the circuit to be considered. Otherwise in fact, the circuit is more metaphysical than physical, a sort of mental image only. I am glad Mr. Hering has tried the experiment, as it will tend to clear up matters which have troubled students in unipolar induction. I have long regarded Faraday's view of *line cutting* as much preferable and more universal than the theory of linkages simply.

The unipolar dynamo is quite practicable for large units of 220 to 550 volts or more, understanding that greater collector losses offset the commutation difficulties with ordinary types and that magnetic losses will probably exceed the calculated losses considerably.

There seems to be one universal law which might be expressed as follows:-"It is not possible without chemical or thermoelectric action to generate a continuous current in a closed circuit without sliding contacts," or "A magnetic induction machine for direct currents must have a commutator or sliding contacts of some sort."

The experiment might be modified by boring holes through the magnet and inserting copper pins, the ends of which would be traversed by the ends of the spring clip. Manifestly since there would be no movement of these pins, there could be no electromotive force generated when they were traversed.

In a magnetic blowout arrester the static stress is exerted at full intensity across the narrower part of the gap in spite of the powerful field surrounding it. As soon, however, as the first slight spark jumps the gap (at the narrower part of course) the gases traversed by the current are deflected. Not, however, until the matter carrying the current has actually bridged the gap does the deflecting action of the field begin.

If the current be assumed to be a flow of electrons (negative) from one molecule to the next contiguous and so on, it is easy to understand why the *matter* of the circuit is the thing concerned and not merely an assumed line or direction.

It may be proper to regard the experiment as involving a form of unipolar induction, inasmuch as it is not possible to use a coil of numerous turns but one of a single turn. If the coil were to be used, it would have to be made up of loops which could open and pass over the magnet by riding upon a series of pins, insulated from each other, projecting through the magnet section, as suggested by me in a modification. Some twenty-five or thirty years ago I leaned to the more generalized view of Maxwell's law referred to in the paper, but gradually grew out of it and adopted Faraday's view of line cutting as the essential thing. The lines must be cut by the moving conductor, or the lines must move and cut the conductor in order to generate an electromotive force, and the potential difference arises in only that section of the conductor which cuts or is cut by the lines.

I think I should have to modify the universal law, which I proposed above, a little in view of Dr. Bruger's direct-current machine. Inasmuch as the resistance of a coil of bismuth wire may be changed by a magnetic field, it is evident that if the magnetism is so used as to increase the resistance of the bismuth when a current in one direction would be induced in it or a part of the circuit in series with it, and if, when the opposite pulse was induced, the resistance of the bismuth were lower, this would amount to a partial commutation but would be accomplished without slipping contacts or any ordinary form of commutator. The result, however, would seem to be more of a pulsating current or a current in which the values of the half waves were unequal, or the wave unsymmetrical with respect to the zero line; a partially rectified current, so to speak. The mercury arc rectifier accomplishes the production of an alternating current from a direct current, and other instances exist, as is well known, of partial rectification by electrolytic cells, vacuum tubes, and the like. It is conceivable that it might be possible to use even a selenium cell in place of the bismuth of Dr. Bruger, putting the selenium in the light at one time and in the dark at another, to affect synchronous alternating pulses differently and give a balance of direct current. A partially rectified current can be sifted so that the direct-current component goes one way, and the alternating-current component another way, as by connecting the terminals by a non-inductive resistance and connecting the direct-current receiving apparatus from the same terminals through a high inductance.

In my paper many years ago, on "Magnetism in its Relation to Induced Electromotive Force and Current" read before the American Institute of Electrical Engineers, I rather emphasized the view that a line of force can only finish by collapsing to a point or infinitesimal closed chain, and can never be broken or opened. By this view, to my mind, we have the only possible explanation for the varied phenomena of induction; that is, we have the only possibility of getting any good physical conception of what takes place.

**W. S. Franklin** (by letter): What is said in this paper concerning the law of induced electromotive force is, I think, entirely correct. I must say, however, that I have never looked upon Maxwell's statement of this law in a way which would lead me to think of it as not strictly correct. It has always seemed to me that the differential equations of the electromagnetic field in *stationary* and in *moving* media cover the ground completely without any possibility of a misunderstanding.

The point of view of looking upon the circuit as abstracted from definite identifiable material may be illustrated in its extreme form as follows: imagine a sheet of copper placed at right angles to a steady magnetic field; imagine an electric circuit in the form of a circle which starts at a point on the copper sheet and spreads outward like a circular ripple on the surface of a pond. This moving circuit, according to Mr. Hering's interpretation of Maxwell's generalization of Faraday's law, should have electromotive force induced in it, and therefore the stationary sheet of copper in a steady magnetic field should have eddy currents circulating in it. Of course I understand it is precisely this absurd conclusion that is being objected to. My point is this: I do not believe that those who accept Maxwell's generalization have forgotten the idea of *actual cutting of lines of force* by the material of the electric circuit; but it may be said they are likely to be led to forget it because of the form of Maxwell's statement of the generalized Faraday law. Perhaps that is true, and yet the difficulty reduced to its simplest terms is the difficulty of partial differentiation; a physical condition is a function of several independent variables, such, for example, as space and time. One is *obliged* to think of one variable only changing at a time, but one should never for this reason surrender the *knowledge* that all things change together.

**Percy H. Thomas** (by letter): If I understand this paper correctly, the experiment is not conclusive, and for the following reasons: in drawing off the loop, as long as the ends are rubbing on the sides of the magnet, the lines of force may be said to be still within the loop. When next those ends come in contact, preliminary to their separation from the magnet, the galvanometer becomes short-circuited and protected from any influence of a later change of lines in the loop. In other words, the original loop becomes two loops by being connected across the middle. None of the lines of force is evidently in the lower loop; all are in the upper loop. The upper loop is then *broken* by withdrawing the wires entirely from the magnet, which of course will give no deflection. What has really been done, if I understand the experiment, is that a portion of the original loop containing the galvanometer (but none of the lines) has been *cut off* by short-circuiting, from the whole loop while it still contains the lines, and then the main loop has been opened.

**W. P. Graham** (by letter): It is perhaps open to question whether the statements of the law of electromagnetic induction by Maxwell and by J. J. Thomson, as quoted by Mr. Hering, are sufficiently precise. Their lack of precision may be simply illustrated as follows: let a wire be bent round the pole of a magnet so as to form a closed circuit linking the magnetic flux. Now let the ends of the wire be separated and the magnet slipped out between the ends so that the flux ceases to link with the wire. Finally, let the wire be again formed into a closed circuit with which the flux does not link. If this re-established circuit be regarded as the original circuit, the flux through the circuit has certainly changed without inducing any electromotive force in the wire.

I think most of us would regard such an interpretation of Maxwell or Thomson as a quibble. But essentially the same interpretation is made by Mr. Hering in discussing the experiment with the galvanometer and copper strips. As soon as the copper strips strike the iron, the original circuit, made up of copper strips and galvanometer is opened, but a new circuit including copper strips, magnet iron and galvanometer is established. And as long as the copper strips make contact with the magnet, there is no change of flux through this new circuit. When the strips leave the magnet, this new circuit is broken, and the old circuit from which the flux has been removed after opening it, is re-established. A more accurate statement would perhaps be that as soon as the strips strike the iron, the old circuit is opened and a new circuit established, to be followed by an infinite succession of other new circuits as the strips slip over the iron, and that the flux is removed from each one of this succession of circuits, by opening each in turn, and establishing its successors; but that there is no change of flux through any individual circuit of the series so long as that circuit is closed.

I agree entirely with Mr. Hering that in presenting the law of induction to a class of students, the cutting of the flux by the conductor is the point to be emphasized and that Faraday's statement of the law is to be preferred.

**George T. Hanchett** (by letter): It would appear from this that some modification of Maxwell's version of the laws of induction should be made. Let us consider two other methods of trying this experiment. The first of these is illustrated in Fig. 1. The test circuit is slipped over the magnet in the usual manner and the initial deflection is observed. It is then unlinked (?) with the magnetic circuit by the following device: The wires are short-circuited at *A* and the clips at *B* drawn over the magnet limb and removed. There will be absolutely no deflection at the galvanometer as a result of this action, provided, of course, that the short-circuiting is perfect.

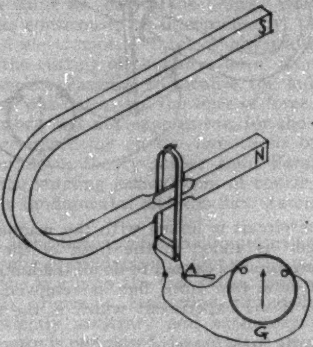

FIG. 1

The second experiment, illustrated in Fig. 2, provides two clips similar to those mentioned by Mr. Hering, but instead of drawing them over the body of the magnet, they are drawn over a tube or annulus surrounding the limb of the magnet and insulated therefrom. It is observed that the detector circuit is first short-circuited outside the flux field before any attempt is made to unlink it, and by this means the circuit is divided into two portions, one containing the galvanometer or detector, which is short-circuited and removed, and the other containing the flux, which is short-circuited and not removed from the magnetic circuit at all. No lines of force are cut by or varied in number within a circuit, and in strict accordance with Maxwell and Faraday no deflection results. In Fig. 2 I have left the loop or ring surrounding the magnet limb in order to point out clearly what Mr. Hering has evidently failed to see—that in performing his experiment he has left an exactly similar flux containing a portion of the circuit behind him in the form of a loop of steel which is a part of the magnet limb itself.

There is no unlinking of the magnetic and electric circuits, but instead a mechanical unlinking which deceives the eye.

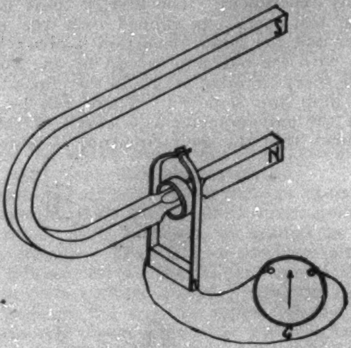

Fig. 2

Electrically, the circuit is linked with the magnet, then a new portion of circuit is added in the form of the magnet limb itself which is ingeniously caused to do all the linking. Next the original circuit now free from flux is removed. This is the exact analogue of the experiment which is the subject of this discussion.

**George A. Campbell** (by letter): The very simplicity of the facts and principles which Maxwell stated is, apparently, the reason for their being overlooked in the present discussion. The points requiring restatement seem to be the following:

1. Electric currents and magnetic lines of force are both closed. This statement is true irrespective of whether the electric conductors and magnetic cores are open or closed. The current is determined by the integral electromotive force around the circuit, and thus any experimental measurement of the current gives us the total, and not the localized electromotive force. An exact statement of fact must then relate only to the integral values for the entire closed circuit; accordingly, Maxwell's statement (Vol. II, paragraph 541) is in terms of these integral qualities:

"The total electromotive force acting round a circuit at any instant is measured by the rate of decrease of the number of lines of magnetic force which pass through it."

This is the fundamental statement of fact, as distinct from theory, in electromagnetic induction.

2. As the current and the lines of force are invariably closed, it follows as a mathematical necessity that the rate of cutting of lines of force by the circuit is equal to the rate of change in the number of lines of force through the circuit. Maxwell expresses this (Vol. II, paragraph 541) as follows:

"If, therefore, the number of lines which pass through a conducting circuit is made to vary, it can only be by the circuit moving across the lines of force, or else by the lines of force moving across the circuit. In either case, a current is generated in the circuit."

The ordinary "cutting of lines of force" statement is thus a derived law and involves something more than the experimental facts. This addition may be merely the mathematical theorem that for any closed circuit the integral result of the "cutting" statement is the same as that of the "flux" statement; or it may also include, consciously or unconsciously, the hypothesis that the induced electromotive force is physically and locally associated with the cutting of the induction. However natural it may have been for Faraday to localize the induction at the point where there was cutting of the lines of force, it is evident that this was theory and not experiment, for the experimental facts may be accounted for on the hypothesis of action at a distance. If Faraday's theory rather than Faraday's experiments is made the starting point, then, of course, "cutting of lines of force" is fundamental and the flux statement becomes the derived law.

3. The law of induction applies to circuits in non-conductors as well as to circuits in conductors. One of the most important applications of the law is to the free ether, where no materials are present. Mr. Hering's restriction to conductors would therefore be perfectly arbitrary and extremely inconvenient. Where the conductor is not closed the circuit is always completed through the dielectric. The induction in the dielectric must always be borne in mind.

4. It is self-evident that the fundamental statement of the law of induction applies to a linear circuit and that it can be extended to a circuit having a finite cross-section only after the system has been resolved into infinitesimal filaments. This principle is an elementary one in applied theory, but its recognition eliminates all difficulty in the application of the flux statement to Mr. Hering's "crucial" experiment. Thus the sketch shows the springs in the process of sliding over the magnet, which is resolved into a network of conducting filaments. As it is found to be immaterial how this resolution is made in the present case, a simple illustrative network is all that is attempted in the sketch. In the experiment, all of the induction passes through the iron and none of it through circuit 1. Motion of the springs does not change the number of lines

of force threading circuit 1 or circuit 2 or any of the remaining 17 circuits. Therefore, the integral electromotive force around each circuit is zero; and no currents can flow; hence the experimental result.

5. When it is possible to state a law in more than one way it is ordinarily true that the application of the law to different problems will be facilitated by the choice of different forms of the law, and that this is the case with the law of induction is not surprising or significant. As Mr. Hering happened on a unipolar experiment, he found the cutting statement more convenient, as have others before. Had he happened upon an experiment involving toroidal coils or slotted armatures, he would presumably have advocated the flux statement.

6. Mr. Hering's new machine is actually a unipolar dynamo. Faraday in his machines, preferred to make both the cutting of lines of force and the sliding of contacts perfectly uniform; this condition seems to be the ideal one and it is now being found to be commercial. Obviously this particular arrangement is not necessary. This is Mr. Hering's machine, while the induction cut by each spring is (on the whole) in one direction throughout the motion, the cutting and the sliding of contacts are made intermittent and alternate with each other. The expectation aroused at the beginning of Mr. Hering's paper, that the limitations of the magnetic induction machine were about to be extended, meets with disappointment. It still remains true that for a direct-current machine magnetic induction alone is not sufficient; sliding contacts, a commutator, a variable resistance or some other auxiliary device is necessary.

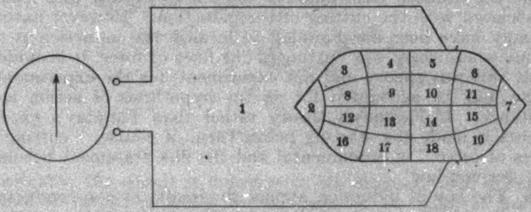

FIG. 1

To summarize: The "flux" law is a literal statement of the observed facts of electromagnetic induction and enables the results to be predicted in any case whatsoever. The unipolar induction experiment described by Mr. Hering presents no exception to this rule and throws no new light upon the subject. The "cutting of lines of force" statement may be regarded either as a mathematical substitute for the "flux" statement, or as a theory localizing the observed action. Both statements of the law are useful in practice.

**Tracy D. Waring** (by letter): Any great generalization when concisely worded is a likely cause of misapprehension. The novel and ingenious experiment by which Mr. Hering links and unlinks magnetic flux into and out of an electrically closed conducting circuit without producing any inductive effect should go far towards removing a prevalent misunderstanding or misinterpretation of the law which for brevity we may term the Linkage Law of electromagnetic induction.

In considering some of the questions raised by Mr. Hering, it would seem appropriate to call to mind the physical conceptions as to the nature of electromagnetic induction from the point of view of electromagnetic theory.

In any circuit undergoing electromagnetic induction, the electromotive force produced in that circuit is due to, or rather owes its existence to, the electric intensity[1] developed at some or all of the points of the circuit. The seat of the electric intensity (electromagnetically produced) can only be at that place in a medium where the magnetic field is in some way changing relatively to the medium, so we may perhaps describe electromagnetic induction thus: Consider any point of a medium in which a magnetic field is sustained; then electromagnetic induction, if it exists there, may be described as the production of an electric intensity, at the point considered, by a change in the magnetic field at that point.

If this statement be true, what shall we understand by a change in a magnetic field at a point? How is such a change to be specified and by what physical conception may we picture it?

An adequate answer to these questions, if such be possible, would involve a complete physical theory of the ether and matter, a problem so profound and vast that the considerations here presented have by comparison but slight significance. These considerations are ventured, however, as laying stress on a certain aspect of the common conceptions relating to electromagnetic induction.

Taking the case of a magnetic field in an isotropic medium having unit permeability (that is, a medium in which the magnetic intensity and the magnetic induction are numerically identical), how shall we describe a change of the magnetic state at a point in such a medium and the related electric state or electric field accompanying the change of magnetic field? The magnetic field has at every point intensity and direction, either or both of which may change. A change of magnetic intensity at the point will suffice to produce an electric intensity there, the directions of the electric and the magnetic intensities being so related as to be at right angles to each other. But that is not all. Both the magnetic intensity and its direction may remain constant and yet some change in the magnetic field may take place, at a point in the medium, that will produce an electric intensity there. Relative motion between the magnetic field and the medium will do this. Such relative motion then also represents a change in the magnetic field at a point.

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[1] Also variously termed electromotive intensity, electric force, and intensity of electric field.

But how shall we picture such motion? Consider any point or points of a medium in which a uniform magnetic field is sustained. Conceive, if you can, a relative translational motion of the uniform field with respect to the point or points fixed in the medium. The magnetic intensity and its direction are everywhere constant, and no instrument fixed in the medium and indicating only intensity and direction would give any indication that the field was moving; yet we can hardly doubt that something does, or may, move relatively to the medium and that the medium responds by having an electric intensity produced in it (unless the line of motion happen to coincide with the direction of the magnetic intensity).

By what physical conception can we make such relative motion have a physical meaning? Perhaps we may put it as follows: Intensity and its direction, as we measure them, do not fully specify a magnetic field at a point. It is not to be expected that so simple an expression could give more than the faintest clue to the physical state we call magnetic, for even a so-called uniform field is not really uniform for very minute dimensions—let us say, for instance, for dimensions of atomic size or perhaps much smaller. If we could only see closely enough, we would see that a so-called uniform field possesses some sort of polarized structure, magnetic filaments of some sort all running the same way and perhaps uniformly spaced.

And so we appear compelled to fall back on a conception of lines of force or tubes of induction having some sort of a real physical existence, if the relative motion between a uniform field and the medium in which it is sustained is to have physical significance.

Take a simple concrete example, say a uniformly magnetized permanent magnet, shaped something like the letter C, with pole faces broad and flat and not very far apart (see Fig. 1). Let the surrounding medium be a dielectric, insulating oil for instance, which we shall suppose remains quiescent around the fixed point, *P*.

The field near the center of the pole faces is practically uniform. Nearer the edges its intensity is weaker and changes in inclination, that is, in direction. Now what happens as the magnet moves forward, relative to the point *P* fixed in the oil, and in the direction indicated by the arrow? It is not difficult to conceive of the magnetic state being created in front of the poles as the magnet advances, and the same kind of state disappearing or being destroyed behind them, while in that part where the field is uniform the magnetic state is constant and apparently does not in any way change as the upper pole face passes over and the lower one under it. But consider the matter more closely. Imagine a minute but intelligent being, stationed at *P*, equipped with an instrument suitable for indicating to him the intensity and direction of the magnetic field. Watching his instrument as the magnet begins to approach him, he sees the magnetic intensity growing stronger and stronger and ever changing in direction (inclination), but presently it reaches a maximum and remains constant in magnitude and direction. He is then in that part of the field which we call uniform. But is that state, which we call magnetic, really at rest about him? Could he perhaps not see, with a wonderful imaginary eye, the magnetic filaments or magnetic whirls or lines of stress or flow or whatever they are—could he not see them file past him as the pole faces move above and below him, or, as a last resort, could he not devise an instrument that would indicate an electric intensity in the field about him?

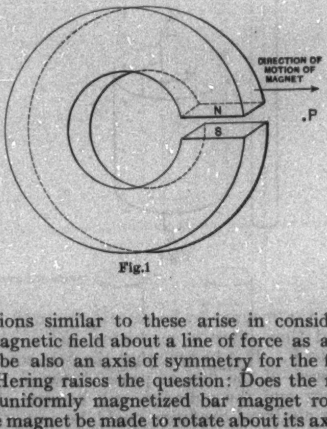

Fig.1

Considerations similar to these arise in considering the rotation of a magnetic field about a line of force as an axis which happens to be also an axis of symmetry for the field. For instance, Mr. Hering raises the question: Does the magnetic field of a round, uniformly magnetized bar magnet rotate with the magnet if the magnet be made to rotate about its axis by mechanical means? Here for any given point in the field the magnetic intensity is constant in direction and magnitude, whether the field rotates or remains stationary?[2]

Sir Oliver Lodge believes that the field does rotate with the magnet, or at least he says: "If a magnet were spun on its axis rapidly by mechanical means, there is very little doubt but that it would act on charged bodies in its neighborhood, tending to make them move radially either to or from it. This, however, is an experiment that ought to be tried; and the easiest way of trying it would be to suspend a sort of electrometer needle, electrified positive at one end and negative at the other, near the spinning magnet, and to look for a trace of deflection—to be reversed when the spin is reversed. A magnet of varying strength might be easier to try than a spinning one."[3] Mr. Hering suggested the use of a single wire and a condenser for an experiment of a similar character.[4]

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[2] We are of course not considering enormous hypothetical peripheral speeds, such as would be comparable with the rate of propagation of magnetic disturbances.

To fix our ideas, imagine the arrangement indicated in Fig. 2, which represents a bar magnet capable of rotating around its axis and encircled by two concentric and coaxial cylindrical conducting surfaces. The two surfaces, which we may look upon as the two plates of a cylindrical condenser, are fixed in space, while the magnet may be made to rotate by some mechanical means not indicated in the figure.

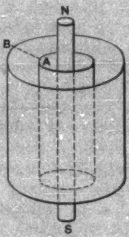

Fig.2

Now assume the magnet to be rotating around its axis at a high speed and then place a conductor, say a piece of wire, across from $A$ to $B$. If it be true that the field rotates with the magnet, then such of the flux as passes between the cylinders will cut the wire and the cylinders will become charged electrically. Their electrical condition could be investigated after first removing the wire and then allowing the magnet to come to rest.

The experiment might perhaps be modified so as to get cumulative results by means of water-drop collectors as in Fig. 3. With this arrangement the magnetic flux of the rotating field cuts the wire, establishing an electromotive force between the ends *a* and *b*, in consequence of which the water-drops at the extremities of the conductor take on opposite electrical charges. The charges are carried off by the water-drops, and the latter in turn give up their charges to the collecting cylinders which should become more and more heavily charged.

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[3] Modern Views of Electricity, Section 73, 1907 edition, by Oliver Lodge. Also see Lodge, *Phil. Mag.*, June 1889, page 469.

[4] A New Factor in Induction; the "Loop" *versus* the "Cutting Lines of Force Law", by Carl Hering, *Electrical World*, March 14, 1908.

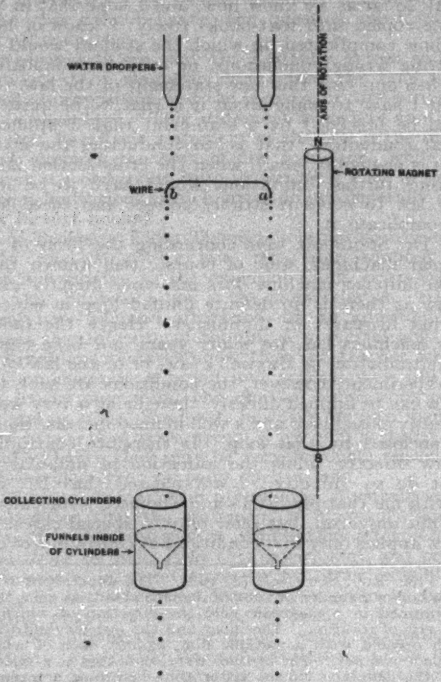
WATER DROPPERS
AXIS OF ROTATION
N
ROTATING MAGNET
WIRE
b
a
S
COLLECTING CYLINDERS
FUNNELS INSIDE OF CYLINDERS

Fig.3

Of these suggested experiments that proposed by Lodge is perhaps of the greater theoretical interest, as it could be performed in some suitable dielectric without perhaps using any conducting material in the field, and is in line with the experiment so successfully carried out by Dr. H. A. Wilson in which he measured the electric displacement in a dielectric resulting from its motion in a magnetic field.[5]

**Carl Hering** (by letter): Concerning Dr. Steinmetz's remarks, I am greatly pleased to see that he agrees with me on the main points. The statement of the general law of electromagnetic induction which he gives is probably the first statement which has ever been published of a form of the law which is really universal, so far as we know now, and I hope that in the future it will be copied into text-books freely; I know of no case, no matter how complicated, in which the student would be misled into getting wrong conclusions, or even only doubtful conclusions, when applying this new statement of the law. The only comment I have to make about it is that, to be quite accurate, it should be preceded by a statement that it applies only to elemental conductors, that is, to conductors the cross-section of which is negligibly small; when the cross-section is relatively large, some further limitations would have to be introduced into the law to make it strictly correct and these limitations would complicate it.

What Dr. Steinmetz says concerning the form of induction in unipolar machines, was, of course, well known to me, but the usual unipolar machine does not come directly under Maxwell's law as there is no definite limited loop in which the enclosed flux increases or diminishes. Hence the induction in unipolar machines has, for many years, not been considered a direct contradiction of Maxwell's law, or of the law of linkages. In my experiment, however, the conditions are such that Maxwell's law can be applied directly, there being a very well-defined permanently closed loop and a well-defined increase and decrease of flux enclosed by that loop. It therefore contradicts Maxwell's law directly, while the induction in unipolar machines does not do so, directly. I am pleased that Dr. Steinmetz agrees with me that Maxwell's and Thomson's statements of the law are not universal, but refer only to special cases. If Maxwell's law applies only to " conditions of continuity of conductor and continuity of motion", as Dr. Steinmetz states it, this limiting condition ought always to accompany the statement of Maxwell's law; but this is not the case in most text-books; and the student should not be left to find out these limiting conditions himself.

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[5] See Proc. Roy. Soc., vol. 73, 1904. The experiment consisted in rotating a hollow cylinder or tube of ebonite about its axis, the rotation being performed in a magnetic field the direction of which coincided with the axis of rotation. The inner and the outer cylindrical surfaces were each covered with a metallic film, against each of which sliding brushes made contact. The brushes were connected to a quadrant electrometer, the deflection of the latter thus becoming a measure of the charge displaced through the walls of the cylinder.

The results indicated that an electromotive force was produced between the inner and the outer conducting cylindrical surfaces the same as though a conductor had been used instead of ebonite, but that the value of the electromotive force was less for the ebonite in the ratio of $\frac{K - K_0}{K}$; $K$ being the electric permitivity of the ebonite and $K_0$ that of free ether, that is numerically $K_0 = 1$ when $K =$ the specific inductive capacity of the moving dielectric (in this case ebonite).

See also Blondlot, *Journal de Physique*, January 1902.

Dr. Steinmetz's description of why a magnetic field remains fixed in space while the magnet generating it revolves on its axis is interesting. It seems, however, that high authorities differ on this point,* hence, the question must still be considered an open one.

I am pleased to see that Dr. Kennelly agrees with me that the movement of magnetic flux across the boundary is the primeordial proposition and the increase or diminution of flux in a loop is secondary. This statement is merely another way of saying that Faraday's statement of the law is the fundamental one and explains the seat of the induction, while Maxwell's statement is a deduction from it, applying only to special cases with strict limitations (which latter do not generally accompany the law in text-books).

One of Professor Elihu Thomson's remarks, namely, that he formerly used Maxwell's law, but later adopted Faraday's view of line cutting as the essential thing, bears out the contention that Faraday's law is the more reliable. His proposed universal law, followed afterwards by an admitted exception, illustrates the difficulty of framing a universal law.

Dr. Franklin's remarks show that the teacher who looks at these phenomena in a broad and general way will be apt to supply in his own mind the omitted limitations of a briefly stated law or rule. Students, however, as also many who are engaged in practical work, accept a law as it is stated and apply it literally; hence they may be very seriously misled unless the limitations clearly accompany such a law.

Mr. Thomas's remarks, in my opinion, illustrate very forcibly my contention that the statement of Maxwell's law is imperfect; for if it requires such a complicated interpretation as he gives in order to make it fit this experiment, and perhaps even more intricate interpretations to fit other possible cases, it certainly is not in correct form to be given to students and practicing engineers to use as it reads. A careful student reading Mr. Thomas's explanation, would naturally feel great uncertainty in applying Maxwell's statement of the law to other unusual cases before he knew the result. If, in this experiment, the continuously closed circuit must be considered as being broken (as Mr. Thomas states in italics), then it must necessarily follow that in all other sliding contacts, such as those on alternators, revolving fields, induction motors, etc., the circuit must be considered to be broken all the time. Hence the current is flowing through a broken circuit without causing an arc—which, of course, leads to an absurdity.

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* See Modern Views of Electricity, Lodge, 1907, Section 73, page 142. Also A Treatise on Magnetism and Electricity, Andrew Gray, 1898. page 329, Section 423, in which the author says: " When the magnet moves, its field of force moves with it."

Replying to Mr. Graham, I need only say that the experiment deals only with permanently closed circuits through which a steady current could be flowing all the time. Hence his analogy to a circuit which is opened and the flux moved out through the opening, is not legitimate discussion of the experiment itself.

Mr. Hanchett's first experiment is essentially different from mine and has no bearing on mine, as it distinctly opens and closes a circuit at a switch. His second experiment is described in my paper, Fig. 3. It seems that Mr. Hanchett has evidently failed to see the very point of the experiment, which was that in teaching students the laws and rules for their practical use, these laws and rules should be so stated that the student will readily understand them, can feel absolute reliance in them, can predict results with certainty and reliance, and will not have to resort to complicated interpretations (like leaving a part of a circuit behind notwithstanding that all of it has been visibly removed) in order to make the laws fit special cases after experimental investigation has shown what the result is.

Mr. Waring's suggestions of methods to determine whether a field moves with its magnet or not, are very ingenious, particularly the one with the water-drop collectors, which it seems to me would not be difficult to carry out. As the result is a simple question of fact concerning which the theories of able authorities give contradictory results, it would be very interesting to have this experiment carried out. I had suggested the use of condensers for such an experiment, but his water-drop method would give cumulative results, which makes the measurement easier. The precaution of course should be taken to stop the rotation of the magnet before connections are made with the electrometer, so that there could not be any question of a possible induction in any leads, which has heretofore been the great stumbling-block in any direct measurements.

Mr. Campbell's statement that "the current is determined by the integral electromotive force around the circuit" is, in my opinion, an evident fallacy, as every student will know that a current is not determined by the electromotive force, but by the quotient of the electromotive force and the resistance; without a knowledge of the resistance the current is a decidedly indeterminate quantity. In his paragraph 2 he virtually says that "as the current" is "invariably closed, it follows as a mathematical necessity that" there cannot be any such a thing as an open circuit, hence Maxwell's loop law is universal!

Of course if one starts out with the arbitrary assumption that an electric circuit cannot ever be opened, then one thereby incapacitates himself to even consider such a thing as induction of electromotive force in an open circuit. Persons who have been left embarrassed in the dark by an opening of the electric light supply circuit, or whose motors have been stalled for a similar reason, will not have much faith in arguments as to the impossibility of opening circuits. If Mr. Campbell will read Faraday he will find that this distinguished experimenter invariably made experiments first and suggested theories to accord with the facts afterwards. I believe he was never guilty of torturing facts to fit premature theories; he never to my knowledge had to interpret a closed circuit to be open or an open one to be closed, in order to fit a pet theory to the facts. To Mr. Campbell's arbitrary assertion that induction "where no materials are present" is "one of the most important applications" of the law under discussion, it is I hope not necessary to reply; the usual industrial use of induction is to get useful currents, which could not flow where there are no materials to conduct and confine them. Why should we be expected to accept his very arbitrary and non-proved statement (4) that "it is self-evident that the fundamental statement of the law of induction applies to linear circuits" (presumably meaning closed circuits or complete loops, as he described before). Authorities, who are recognized both here and abroad, consider the general case to include all kinds of circuits whether open or closed, the closed circuit being therefore a special case; in order to be fundamental, a law must apply to the general case. Many who have been asked have acknowledged frankly, and in a true scientific spirit, that Maxwell's law as usually stated would not have predicted the correct results of this experiment before the results were known: hence Mr. Campbell's arbitrary statement that it "enables the results to be predicted in any case whatsoever" is not borne out by facts. That the experiment "throws no new light on the subject" is a matter about which others have expressed a different opinion to me. One of the chief objects of my paper was to try to show that there is room for improvement in teaching students the fundamental laws, so that they will obtain such a clear and unencumbered conception of those laws that they will have confidence in applying them for predicting results, without involving complicated "interpretations"—such as having to consider an open circuit to be a closed one, or the reverse—which require an experimental determination before a correct prediction can be made. Mr. Campbell's discussion is a good illustration of this.

Mr. Thomas has claimed above that what is universally considered by electrical engineers to be a closed circuit must now be considered to be an open circuit in order to make his theory fit this case, and now Mr. Campbell claims that what would generally be considered to be an open circuit must now be considered to be a closed one in order to make his theory fit this case. I think this is a good illustration of the point raised in the paper, that Maxwell's law is not in a satisfactory form for teaching students, or for engineers to use.

A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 2, 1908.

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# GRAPHICAL TREATMENT OF THE ROTATING FIELD

BY R. E. HELLMUND

The object of this paper is to evolve diagrams by means of which nearly all the phenomena of the rotating field may be easily studied, and the various factors necessary for the calculation of fluxes, exciting current, etc., exactly determined. In order to avoid too frequent repetition of certain expressions, the author has adopted the expedient of using the words " addition " and " subtraction " to mean geometrical addition and subtraction of vectors according to the well-known conventional method.

The derivation of a full pitch two-phase winding with four slots per pole per phase as represented in Fig. 1 may be chosen. The two vectors $a$ and $b$ in Fig. 2 represent the total ampere-turns of the two phases $a$ and $b$. Under this assumption the ampere-turns of one of the 8 coils of each phase may be represented by one-eighth of each of the two vectors. In Fig. 1 the coils of phase $a$ are numbered from $1a$ to $8a$, those of phase $b$ from $1b$ to $8b$. As in any similar winding the current flows in four coils of each phase in one direction and in the other four coils of the same phase in the opposite direction; the difference of flow is indicated in Fig. 1 by + and − signs in front of the number of the coil.

1. *Diagram of the fluxes in the individual teeth.* Consider, first, tooth number 2. It is seen from Fig. 1, that the coils $-3a$, $-4a$, $+5a$, $+6a$, $+1b$, $+2b$, $+3b$, and $+4b$ exert a magnetizing effect upon this tooth. The effects of the coils $-3a$, $-4a$, $+5a$, and $+6c$ neutralize each other, and therefore the resultant magnetizing effect is in phase with the ampere-turns $b$ and equal to four-eighths of $b$. The resultant mag-

netizing effect may therefore be represented by the vector $\overline{0-2}$ Fig. 3, which is equal to four-eighths of $b$ and parallel thereto. Passing from tooth 2 to tooth 3, it will be seen that the magnetizing effect of coil $-3a$ must be subtracted and that of coil $+7a$ be added in order to obtain the resultant magnetizing effect exerted upon tooth 3; the subtraction and addition may be accomplished by adding the line $\overline{2-3}$, which is in phase with the vector $a$ of Fig. 2 and = two-eighths of $a$, to the line $\overline{0-2}$. The resultant line $\overline{0-3}$ represents the magnetizing effect exerted upon tooth 3. In the same way the magnetizing effects exerted upon all 16 teeth may be easily determined. The square 16-4-8-12 is obtained in this way. If a uniform reluctance over all the poles is assumed, the vectors $\overline{0-1}$, $\overline{0-2}$, $\overline{0-3}$, etc., may at the same time be considered to represent the fluxes in the teeth 1 to 16,* if the scale is changed under proper consideration of the air-gap reluctance, etc.

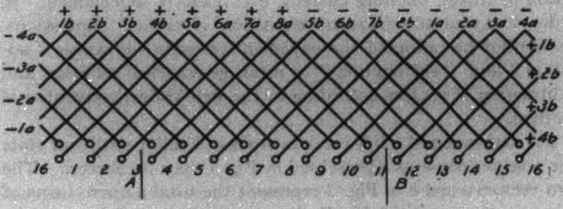

FIG. 1.—Space values of the rotating field.

2. *Diagram of the space values of the total field.* It is obvious that the vector representing the total field over a certain arc of the pole face may be easily obtained by simply adding the flux vectors of those teeth which form part of the arc under consideration. Thus in order to obtain the vector representing the total flux of an arc equal to a full pole pitch, the fluxes of 8 adjacent teeth have to be added. If, for instance, the fluxes of teeth 2 to 9 are added as shown in Fig. 3, we obtain the vector $6a$, which represents the total flux over an arc comprising the teeth 2 to 9; that is, over an arc equal to the pole pitch. In order to find the total flux over the teeth 3 to 10, the complete addition does not need to be repeated; it is only necessary

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* This diagram for the tooth fluxes was evolved by Professor H. Görges, Dresden, and is published in *Electrotechnische Zeitschrift*, January 3, 1907.

to subtract from 6*a* the vector 2 and to add the vector 10; thus the desired vector, 7*a*, which represents the total flux over the teeth 3 to 10, is quickly obtained. In the same way we find:

Vector 8*a* representing the total flux over the teeth 4 to 11
" 5*b* " " " " " " " 5 " 12
" 6*b* " " " " " " " 6 " 13
etc.

The vector for the flux between any two points *A* and *B* on the pole face, which are a full pole pitch apart and which do not coincide with the primary current centers, may be just as easily determined. Suppose, for instance, that the points *A* and *B* are respectively one-third and two-thirds of a tooth pitch away from the next current point. The vector for the flux between the two points may then be found by adding to the vectors of the teeth 3 to 10; that is, to the vector 7*a* a vector equal to two-thirds of the vector 11 and by subtracting a vector equal to two-thirds of the vector 3. Thus the vector *A B* is obtained, representing the flux between the points *A* and *B*. It will be readily seen from this that any line from the center of the diagram to one of the sides of the polygon 6*a*, 7*a*, 8*a*, 5*b*, etc., represents the flux of some arc equal to the pole pitch.

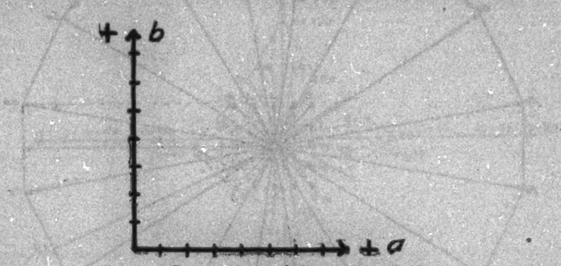

Fig. 2.—Space values of the rotating field.

3. *Diagram of potentials.* After the total flux over any full pitch area of the pole face is determined, the potential induced in a full pitch coil placed around this area may be represented by a vector proportional to and lagging 90 degrees behind the flux vector. If, for instance, the two sides of a secondary coil were placed on the points *A* and *B* the potentials induced in

the coil would be represented by a vector proportional to the vector $A\,B$ lagging 90 degrees behind it. The potentials induced in the primary coils are represented by vectors proportional to and lagging 90 degrees behind the vectors $7a$, $8a$, $5b$, $6b$, etc. The potential vectors corresponding to the field vectors $7a$, $8a$, $5b$, $6b$, etc., are shown in Fig. 4, and correspond to the potentials induced in the coils $7a$, $8a$, $5b$, $6b$, etc., respectively. The total potential induced in the four coils of each group may be obtained by simply adding the four corresponding vectors, as shown in Fig. 4.

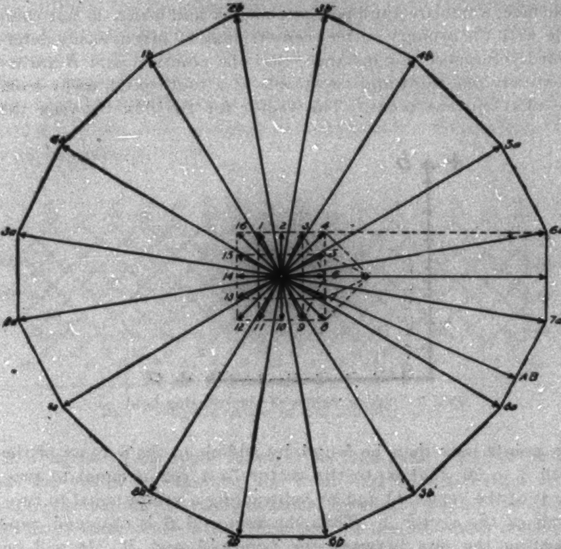

FIG. 3.—Space values of the rotating field.

4. *Diagram of the time values of the total field.* As has been stated, from Fig. 3 can be found the vectors, which represent the maximum values as well as the time-angle of the total fields over any full pitch area of the pole face. It was found, for example, that the vector $A\,B$ represents the maximum flux value between the points $A$ and $B$ of Fig. 1. This flux does

not, however, necessarily represent the maximum flux which exists at the time at which the flux between *A* and *B* reaches its maximum value. It is obvious that there may be fluxes that find some path which does not go through the pole face area between *A* and *B*; or there may be fluxes that pass the pole face between *A* and *B* twice, and which therefore have no effect upon a coil located with its two sides at the points *A* and *B*. The question arises, therefore, what are the maximum

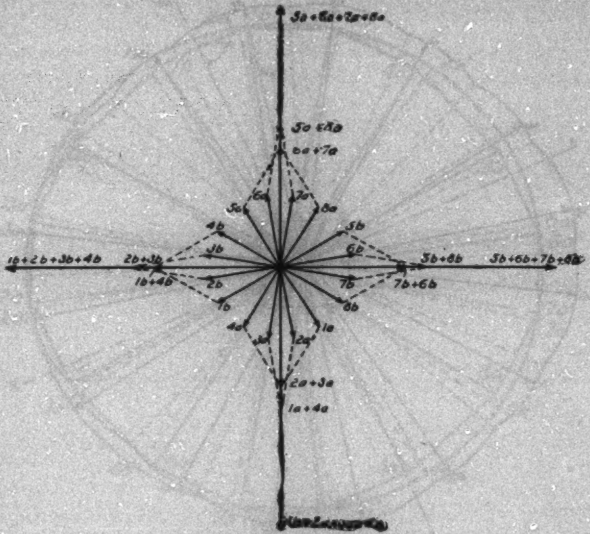

FIG. 4.—Potential diagram.

values of the total field existing at any point of time? (In considering this question the leakage fluxes across the slots and the end connections of the coils may be neglected, since they can easily be considered separately.)

It was found that all the individual fluxes that go through each particular tooth are represented by the vectors 1 to 12 in Fig. 3. The maximum value of the flux at any time must therefore be represented by the sum of all individual fluxes that have the same direction at the time under consideration. If, therefore, in Fig. 5, which contains some of the vectors of Fig. 3, a time-line, $\overline{o\,m}$, is assumed, the maximum field value for this time may be represented by the addition of all the projections of the individual teeth fluxes, which have the same direction, upon the time-line; or, what is equivalent, by the projection of the graphical sum of all the teeth flux vectors that are at one side of the perpendicular, $\overline{x\,y}$, on the time-line. For the time-line under consideration the maximum field value is the graphical sum of the vectors 15, 16, and 1 to 6. The graphical sum of these vectors is represented by the vector 3*b*, as before derived; consequently the value of the total field may be found by projecting the vector 3*b* on the time-line. This holds for any time-line the perpendicular of which falls between the vectors 14 and 15, or between 6 and 7. In the same way the value of the total field for any time-line the perpendicular of

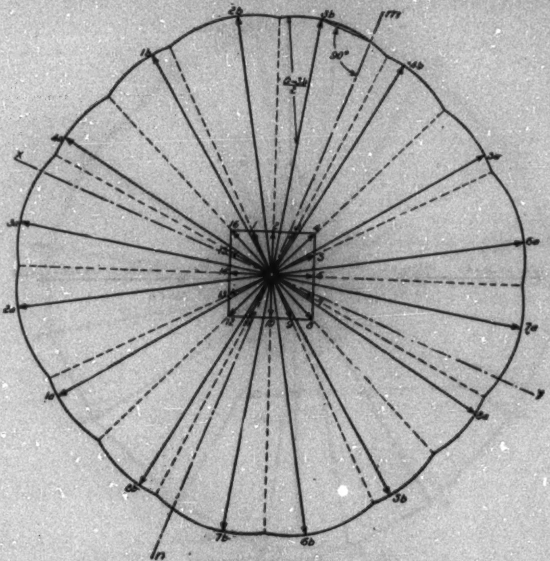

Fig. 5.—Time values of the rotating field.

which falls between the vectors 15 and 16 or between 7 and 8 may be found by projecting the vector 4*b* on the time-line, etc. It is also obvious that the locus of the projection points upon the time-line is a circle around the center of each vector. A very simple polar representation of the total field value in terms of the time-angle may therefore be obtained by simply drawing these circles for all the vectors, as shown in Fig. 5. The intersection of the various circles occurs when the perpendicular to the time-line passes the vectors of the teeth fluxes; therefore the time-angles of the intersection points follow directly from the time-angles of the teeth fluxes.

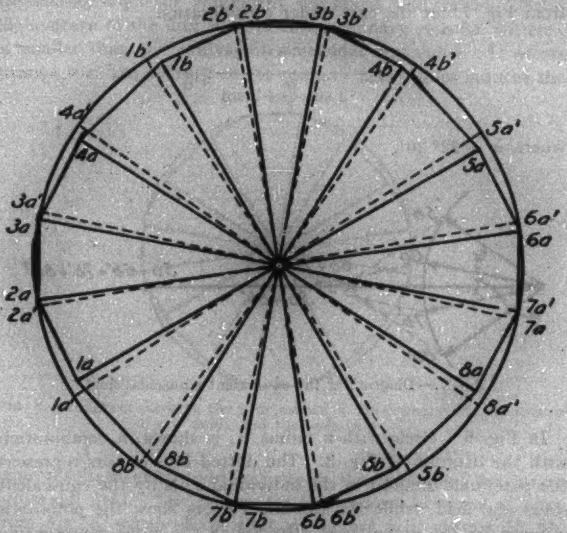

Fig. 6.—Comparison between the actual field and the equivalent sinusoidal field.

5. *Equivalent sinusoidal field*. After the vector representing the total potential which is induced in one group of coils has been found from Fig. 4 to equal *E*, it is possible to find the amplitude of the equivalent sinusoidal field; that is, the size of a field that has a sinusoidal space distribution rotates with

uniform speed and has the same effect as the actually existing field.

If $n$ is the number of coils per pole, the angles between the potentials being induced in the coils is

$$\alpha = \frac{180}{n}$$

Moreover, if the potential induced in each coil is $x$, it follows from Fig. 7, for the case under consideration:

$$x = \frac{E}{2 \sin \frac{\alpha}{2} + 2 \sin \frac{3\,\alpha}{2}}$$

where $\alpha = 22^\circ\, 30'$.

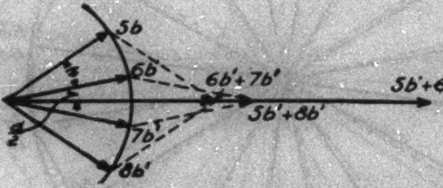

Fig. 7.—Diagram of the equivalent sinusoidal field.

In Fig. 6 a circle with a radius, $x$, is shown in combination with the diagram of Fig. 3. The dotted line vectors represent the potentials induced in the individual coils by the equivalent sinusoidal field, while the full-line vectors show the potentials induced by the actual field. In Fig. 8 the circle representing the equivalent sinusoidal field is shown in combination with the diagram on Fig. 5.

6. *Characteristics of the rotating field.* From the diagrams evolved so far, the main characteristics of the rotating field may be discerned merely by looking at the illustrations. It appears at once from Figs. 3 and 6, that the space values of the field vary in size; from Figs. 5 and 8 it appears that the total time values also vary in size. From the tooth diagram in Fig. 3, it follows that the maximum values of the individual teeth fluxes are different in size, and their time-angles differ

from the angles giving the space distances between the teeth; this means that the individual parts of the field rotate at non-uniform speed. That the total field rotates at non-uniform speed appears from Fig. 6, because the full-line vectors, that is, the vectors of the actual field values, would coincide with the dotted vectors, which indicate the time-angles of a uniformly rotating field, if the total field were to rotate at uniform speed. From Figs. 6 and 8 it also appears that the average of the space values, as well as the average of the time values, are smaller than the equivalent sinusoidal field values. Even the average of the flux vectors of the primary coils 5*a*, 6*a*, etc., is smaller than the equivalent sinusoidal flux value. It seems strange that the average of the primary field values induces the same resultant electromotive force as the equivalent but larger sinusoidal field. The reason for this follows however at once from Fig. 6, which shows that the actual field vectors 5*b*, 6*b*, 7*b*, and 8*b*, for instance, which belong to one group of coils, are less out of phase than are the equivalent vectors of the sinusoidal field 5*b*′, 6*b*′, 7*b*′, and 8*b*′. For this reason it happens that for some coil arrangements the actual field reaches at no time the value of the equivalent sinusoidal field.

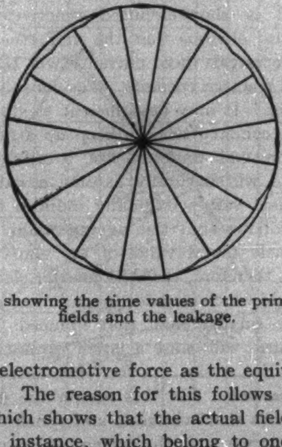

FIG. 8.—Diagram showing the time values of the primary and secondary fields and the leakage.

7. *Reactive effect of the secondary.* So far the diagrams have been evolved and the field treated without considering the reactive effects of the secondary. Assume now that a single coil, which may first be considered to be open-circuited, is rotated at synchronous speed round the pole face. Assume further

that the dotted lines 1a', 2a', 3a', etc., of Fig. 6 represent some time-positions of the rotating coil. They then give the positions of the secondary coil, in which its sides coincide with those of the primary coils 1a, 2a, 3a, etc., respectively. For these positions the time vectors of the fields are represented by the full lines 1a, 2a, 3a, etc., in Fig. 6, and the field inside of the moving coil, while the latter is in position 1a' may be found, for instance, by projecting line 1a' upon 1a', assuming that the sides of the rotating coil happen to coincide with those of the primary coil at the time represented by the vector 1a'. For any other position of the coil the field inside the coil may be similarly found. It will be seen that the field as set up by the primary in the synchronously rotating secondary coil will fluctuate in size; therefore there will be potentials induced in the secondary coil, and if this coil is short-circuited reactive currents occur therein. It is also obvious that the more the polygon differs from a circle the larger these currents will be. The detailed treatment of the reactive currents takes considerable space and will be given later. It may be sufficient to state here that the currents in the secondary tend to keep up a field of sinusoidal space distribution and uniform size rotating with uniform speed. This field will naturally assume a value equal to an average of the field values originally induced by the primary. From Fig. 8 it follows that this average value will be smaller than the previously found value of the equivalent sinusoidal field. It follows, therefore, that the counter electromotive force induced by the field which is under the influence of the secondary reactance will be smaller than that induced by the original field. This, in turn, will cause a larger primary magnetization current in order to make up for the decrease caused by the secondary reaction. For this reason the magnetizing current of a motor with short-circuited and synchronously rotating secondary will be larger than the current of the motor with open secondary. The ratio of the two currents is the ratio of the average time values of the actual field as originally set up by the primary (open secondary assumed) and the value of the equivalent sinusoidal field. This ratio may be called the reactance factor.

8. *Derivation of coefficients.* The above diagrams lend themselves readily to the derivation of such factors as are required for the practical calculation of the rotating field and its magnetizing current. By drawing a segment of the diagram on

cross-section paper, as shown in Fig. 9, the problem of exactly determining the various factors is reduced to simple geometrical calculations, which may be quickly made with the aid of a table giving the squares and the square roots of figures and the angle functions. Various methods of proceeding and various factors may be chosen for the calculation of the magnetizing current and the field. It seems to the writer, however, that the relative merits of each coil arrangement may be best recognized if a coil arrangement with one slot per pole per phase is chosen as a base.

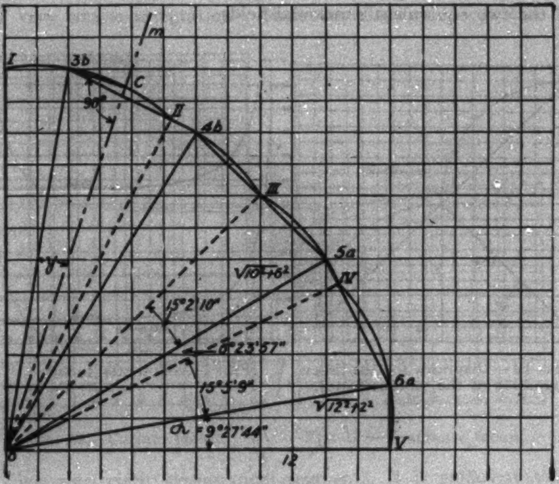

FIG. 9.

*a. Potential factor.* If, for instance, the potential being induced by a given sinusoidal field rotating with a given uniform speed is $E_1$, under the assumption of a given full-pitch winding located in one slot per pole per phase, the potential $E_n$ induced by the same field in the same winding distributed over $n$ slots per pole per phase may be

$$E_n = k_p E_1,$$

where $k_p$ may be called the potential factor. The factor $k_p$ is found from diagrams as shown in Fig. 7, and from the formulas given in connection therewith. The curves of Fig. 11 give the factor $k_p$ for two-phase and three-phase full-pitch windings in terms of the total number of slots per pole.

*b. Current factor.* We assume further that a certain number of ampere-turns in a full-pitch winding wound in one slot per pole per phase induces, in case of an open-circuited secondary, a field, equivalent to the sinusoidal field $F_1$; and that the same number of ampere-turns in case of the same winding wound in $n$ slots per pole per phase induces with an open-circuited secondary a field which is equivalent to a sinusoidal field $F_n$. The ratio of the two equivalent sinusoidal fields,

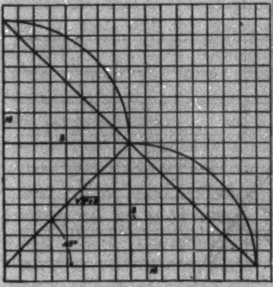

FIG. 10.—Diagrams for the determination of the various factors.

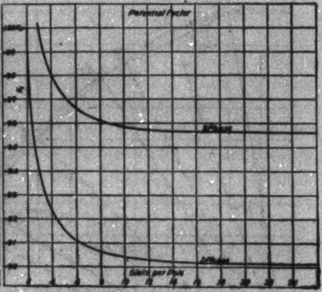

FIG. 11.—Potential factor.

$$k_c = \frac{F_n}{F_1}$$

may then be called the current factor.

The latter may be found by drawing, in addition to the diagram of Fig. 9, the diagram for one slot per pole per phase as shown in Fig. 10, the same number of total ampere-turns being assumed for both cases. The ratio of the equivalent sinusoidal fields found from the two diagrams is then the current factor $k_c$. The curves in Fig. 12 give the current factors for two-phase and three-phase full-pitch windings in terms of the total number of slots per pole.

*c. Reactance factor.* The potential and current factors are sufficient for calculating the magnetizing current with an open-circuited secondary. In order to find the exact magnetizing current for the case of a short-circuited synchronously rotating secondary the previously mentioned reactance factor has also to be determined. For this purpose we have to find the average value of the time values of the total field. From Fig. 9 it is seen that for any time-line, $\overline{O\text{-}m}$, during the time period I–II the time value of the field is

$$O\,C = \overline{O\text{-}3\,b}\cos y.$$

The average value over one period may therefore be found by a very simple integration. Since the diagram in our case has, however, eight symmetrical segments, it is sufficient to find the average value for one of the eight segments. Thus we find the average time value of the field from segment III–IV–V to be:

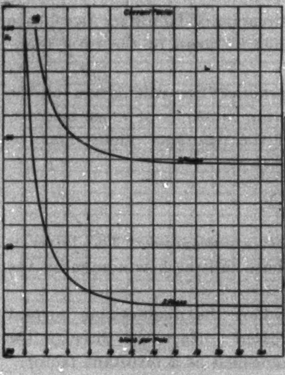

Fig. 12.—Current factor.

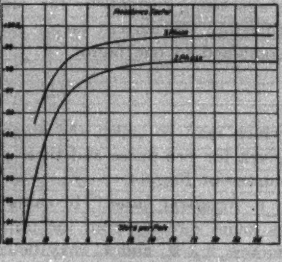

Fig. 13.—Reactance factor.

$$F_a = \frac{4}{\pi}\left[\sqrt{12^2+2^2}\int_{-9^\circ\,27'\,44''}^{15^\circ\,5'\,9''}\cos y \;+\sqrt{10^2+6^2}\int_{-6^\circ\,23'\,57''}^{15^\circ\,2'\,10''}\cos y\right]$$

or

$$F_a = \frac{4}{\pi}\Big[\sqrt{12^2+2^2}\,(\sin 15^\circ\,5'\,9'' + \sin 9^\circ\,27'\,44'')$$
$$+\sqrt{10^2+6^2}\,(\sin 15^\circ\,2'\,10'' + \sin 6^\circ\,23'\,57'')\Big]$$

The various angles may be best found from their tangent, which follows directly from the figure. For the first angle $\alpha$ we have for instance

$$\tan \alpha = \frac{2}{12} \text{ therefore}$$

$$\alpha = 9° 27' 44''$$

The reactance factor is found from

$$k_r = \frac{F_a}{F_n}$$

The curves in Fig. 13 give the reactance factor for two-phase and three-phase full-pitch windings in terms of the total number of slots per pole.

*d. Magnetization factor.* In practice the calculation of the magnetizing current for the running motor is of most interest, therefore the current factor and the reactance factor may be combined to one factor

$$k_m = k_r \, k_c,$$

which may be called the magnetization factor. The latter is given for two-phase and three-phase full-pitch windings by the curves of Fig. 14.

*e. Resultant factor.* In cases where the magnetizing current is found directly from the impressed voltage, all three of the factors, $k_p$, $k_c$, and $k_r$, may be combined as a resultant factor

$$k = k_p \, k_c \, k_r$$

The latter is given for two-phase and three-phase full-pitch windings by the curves of Fig. 15.

9. *Calculation of the field and its magnetizing current.* In practise the impressed potential is known as a rule, and the field and its magnetizing current are to be determined. If $F_1$ is the required sinusoidal field for the one slot per pole per phase arrangement, we find for other arrangements:

*a.* For open-circuited secondary:

The equivalent sinusoidal field $F_n = \dfrac{F_1}{k_p}$

The average of the time values of the actual total field

$$F_a = \frac{F_1}{k_p} \times k_r$$

*b.* For short-circuited and synchronously rotating secondary: The equivalent sinusoidal as well as the actual field

$$F_n = \frac{F_1}{k_p}$$

If $I_1$ is the required magnetizing current for open-circuited secondary with the one slot per pole per phase arrangement, we find for other arrangements:

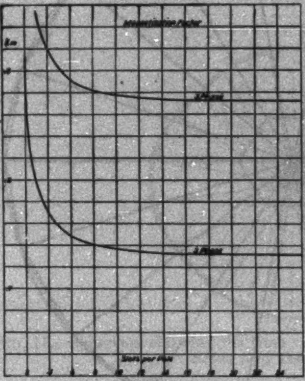

FIG. 14.—Magnetization factor.

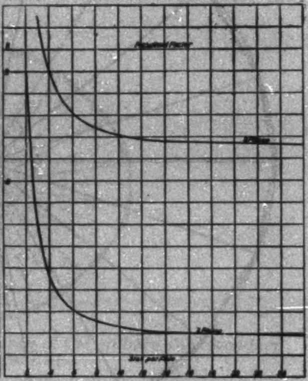

FIG. 15.—Resultant factor.

*a.* For open circuited secondary:

$$I_n = \frac{I_1}{k_p \times k_c}$$

*b.* For short-circuited synchronously rotating secondary

$$I_n = \frac{I_1}{k_p \times k_c \times k_r} = \frac{I_1}{k}$$

10. *Magnetic leakage.* The diagrams also give a means for deriving the magnetic leakage. The time values of the total fluxes in the secondary may be determined similarly to the time values of the primary flux, by finding the vectors for the fluxes in the secondary coils and drawing circles round their centres.

Let us assume, first, that the secondary has the same number of slots as the primary, and that the secondary is in a position

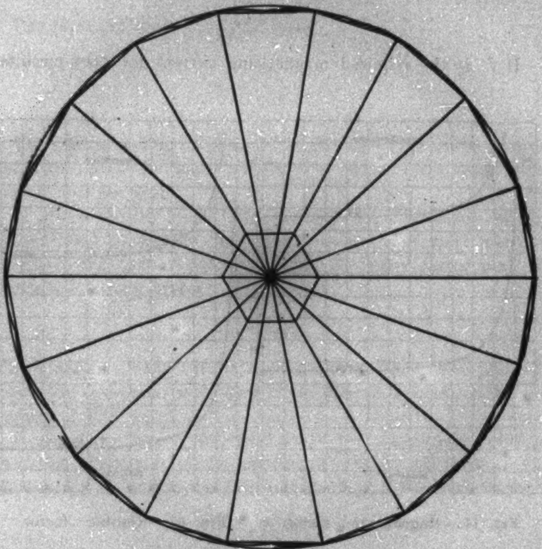

FIG. 16.—Field diagrams for a three-phase motor with three slots per pole per phase.

in which the sides of the coil coincide with those of the primary. Then of course the secondary fluxes are always the same as the primary fluxes, and the potentials induced in the secondary are the same as in the primary, slot and end-connection leakage being neglected. Therefore the curve of Fig. 8 represents for this case the primary flux as well as the secondary flux; that is, the leakage flux is zero.

The rotor may now be shifted so that the sides of its coil are located in the middle between the coil sides of the primary. The field vectors of the secondary are then represented by the dotted lines of Fig. 17, which go from the center of the diagram to the middle points of sides of the polygon. By drawing the circle segments around the centers of these dotted lines, we obtain the inner curve shown, Fig. 17, which represents the time values of the total secondary flux. The difference between the outer and the inner curve represents the leakage flux for the rotor position under consideration.

In Fig. 18 the same curves are shown for a secondary position between that of Figs. 8 and 17. The three figures show clearly the change of the leakage field with the secondary position.

In Fig. 19 the curves for the fluxes are shown for a rotor in a position like that of Fig. 17, the number of secondary slots being reduced to half their former number. A comparison with Fig. 17 shows at once how the leakage has increased by the reduction of the secondary slots.

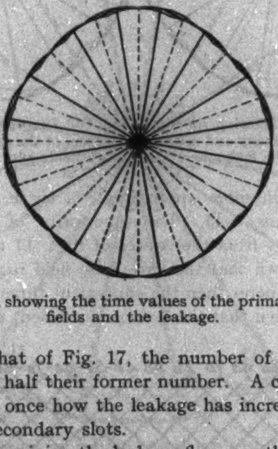

FIG. 17.—Diagram showing the time values of the primary and secondary fields and the leakage.

Instead of determining the leakage fluxes as the difference between the primary and secondary fluxes, the zig-zag and belt leakage fluxes may be also determined directly from the diagram of the teeth fluxes. The slot leakage may also be determined by the latter.

11. *Comparison between two-phase and three-phase fields.* It may be well to give for the purpose of comparison, a diagram for a three-phase winding. Fig. 16 shows the diagram for the teeth fluxes, the space values, and the time values of the total

fluxes of a motor with three slots per pole per phase; that is, approximately the same number of slots per pole as for the two-phase case considered before—nine slots per pole instead of eight. It appears at once from the diagram that the three-phase field approaches the ideal condition much more than does the equivalent two-phase field. All three diagrams given in Fig. 16 give curves that much more approximate a circle than the curves for the two-phase field. The superiority of the three-phase field also appears from the curves of Figs. 11 to 15.

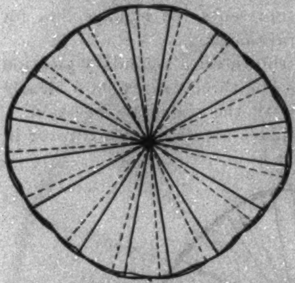

FIG. 18—Diagram showing the time values of the primary and secondary fields and the leakage.

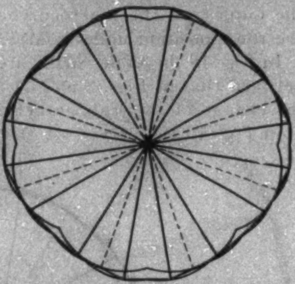

FIG. 19—Diagram showing the time values of the primary and secondary fields and the leakage.

It is well known that the two-phase field requires more magnetizing volt-amperes than the equivalent three-phase field. It may also be shown that the leakage coefficient of the two-phase field is larger than that of the three-phase field. These facts are considered by every designer, and result in the well known differences of 0.5 to 3 per cent. in the calculated values of the efficiency and power-factor, or possibly in some difference in the starting torque and pull-out torque of the two motor types, if they are designed for equal power-factor.

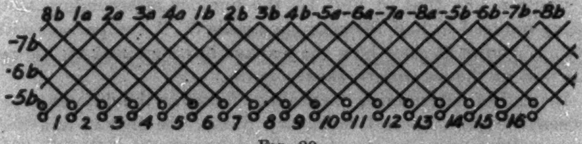

FIG. 20.

The comparison of the above diagrams shows, moreover, that a two-phase motor will have larger reactive currents in the secondary. The comparison of the reactance factors shows that the amplitude of the higher harmonics in the primary is larger in the two-phase motor than in the three-phase motor. Consequently both of the latter phenomena tend to reduce the efficiency of the two-phase motor more than that of the three-phase motor;

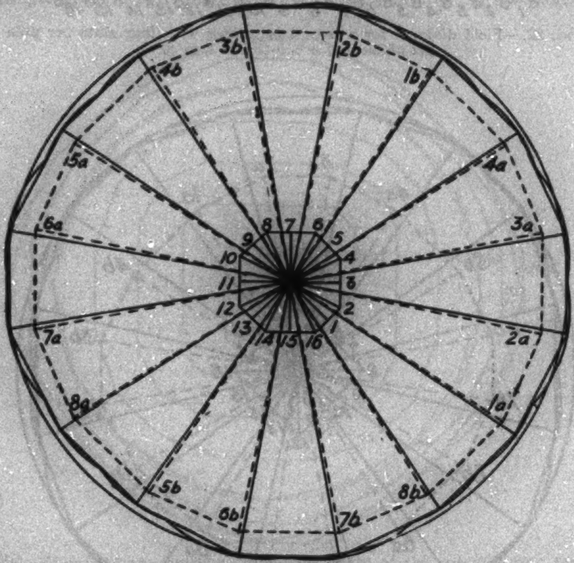

FIG. 21.—Field diagram for a two-phase motor with four slots per pole per phase and a coil-throw 1 to 7.

12. *Fractional pitch.* The diagrams may also be applied to fractional pitch windings. Fig. 20 shows a two-phase winding with four slots per pole per phase and 75 per cent. pitch. Fig. 21 gives the diagram for this winding. The inner small polygon gives the individual teeth fluxes; the outer polygon gives the space values of the field; the curve consisting of segments of circles gives the time values of the total field. These three

figures are derived in the same manner as that previously shown for full-pitch windings. Since in the case of fractional pitch windings the fluxes interlinking with the primary coils are smaller than the total primary fluxes, it is necessary to find the time

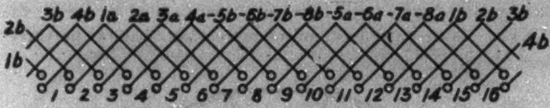
3b
4b
1a
2a
3a
4a-5b-6b-7b-8b-5a-6a-7a-8a
1b
2b
3b
2b
1b
4b
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

FIG. 22.—Field diagram for a two-phase motor with four slots per pole per phase and a coil-throw 1 to 5.

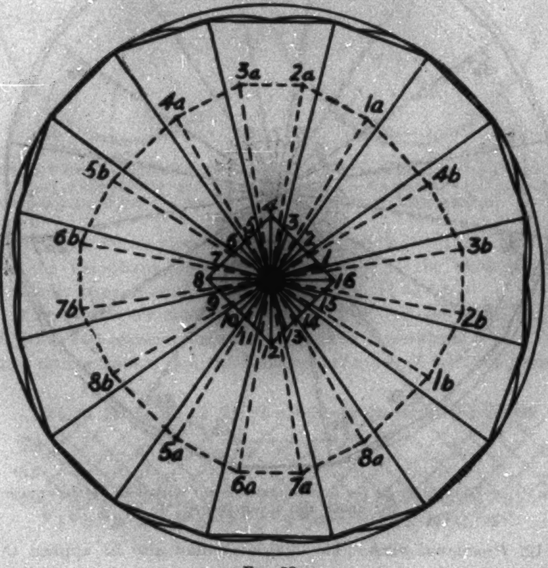
3a
2a
4a
1a
5b
4b
6b
3b
7b
2b
8b
1b
5a
8a
6a
7a
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

FIG. 23.

values of the fluxes interlinking with the primary coils in order to find the potentials induced in the primary coils. These fluxes are found for each coil by adding the fluxes of the teeth, surrounded by the coil under consideration. The primary coil fluxes thus obtained are shown in Fig. 21 by the vectors 1*a*, 2*a*, etc., which corresponds to the coils 1*a*, 2*a*, etc., of Fig. 20 respectively. The various factors may be derived in the same way as before for the full-pitch windings. The equivalent sine field is represented in Fig. 21 by the circle.

Figs. 22 and 23 give the same slot arrangement as before with a two-phase 50 per cent. pitch winding.

In Fig. 24 the diagrams for the space values of the field for all pitches for two phase 8 slots per pole between 0 per cent. and 100 per cent. are shown. The numbers given indicate the throw of the coils, for which the various polygons apply. It appears that the full-pitch polygon throw 1 to 9 is flattened in a direction 45 degrees to the horizontal and vertical. The same applies to a smaller extent for the 87.5 per cent. pitch —throw 1 to 8— and the 75 per cent. pitch—throw 1 to 7—windings. For the 62.5 per cent. pitch—throw 1 to 6— winding the polygon is closest to a circle. The circle is shown here only for comparison. If the pitch is reduced further, the polygons

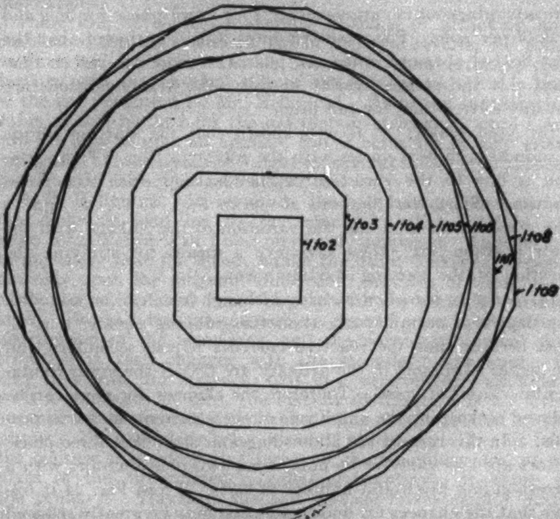

Fig. 24.—Diagram showing the space values of the rotating field for various pitches.

become flattened in the vertical and horizontal direction and the flattening becomes the larger the more the pitch is reduced. This means that by reducing the coil pitch from full pitch, the field may be improved to a certain point; it will, however, become worse again if the pitch is reduced below a certain amount. Without delving further, it may be safely concluded that for the 75 and 62.5 per cent. pitches the secondary reactive currents and the higher harmonics in the primary are the smallest. It may be also shown that the leakage coefficient for this pitch is reduced. The 75 and 62.5 per cent. pitches are therefore advantageous in various respects for a two-phase winding and 8 slots per pole. For most windings it will be found that the best field is obtained when the phases overlap one-half to one-third. If the phases overlap entirely, the field conditions are not any better than for full pitch.

13. *Dead points.* It is well known that the starting torque of induction motors varies with the rotor position. This variation is due to the variation of the leakage with the rotor position. Since the diagrams shown in Figs. 8, 17, 18, and 19 give a means for studying the variation of the leakage with the rotor position, etc., they also give a means for studying the question of the varying starting torque.

14. *Noise in induction motors.* Although little can be said with any degree of certainty about motors running noisily, it is almost certain that the reactive currents in the secondary and the higher harmonics in the primary are two of the many fundamental causes of noise. Therefore the chances for noise can be reduced by keeping the amplitude of these currents as low as possible. In this respect the above diagrams show that three-phase motors are less likely to be noisy than two-phase motors with a corresponding pitch and number of slots. From Fig. 24 it follows that the chances for noisy operation may be greatly reduced by choosing the proper pitch; in the case under consideration the pitches are 75 and 62.5 per cent.

While it has not been possible to treat in this paper the various topics much in detail it will be readily seen that the graphical method before outlined will answer a great many questions. Moreover, the graphical treatment always has the advantage of giving a clearer conception of the physical facts than analytical formulas. The analytical treatment is rather complicated and requires in many cases too much time.

## DISCUSSION ON "GRAPHICAL TREATMENT OF THE ROTATING FIELD." ATLANTIC CITY, N. J., JULY 2, 1908.

**Comfort A. Adams:** This is not an easy paper to discuss, for although it presents many familiar phenomena, it presents them in a new language with which it takes time to become familiar. It is a very good kind of language, however, as it assists greatly in visualizing the problem in hand. This is of value, not only to the beginner in getting a picture of what goes on, but to the man who has to make the calculations, because when he can see the problem clearly in his mind's eye he is far more apt to get accurate and reliable results from his calculations.

There are, of course, numerous methods of attacking any problem of this kind, with similar or identical results, but some methods are far more valuable because of their intimate connection with the physical side of the subject and this is true of the one presented by Mr. Hellmund. As to the comparative value of this method for the calculation of leakage, etc., I am not yet able to give an opinion, but it certainly is very interesting and throws much new light on several rather troublesome problems in induction motor analysis.

**R. E. Hellmund:** In regard to the belt leakage phenomena, the diagrams lead me to the conclusion that matters are more complicated than I had previously supposed. It occurred to me lately that the latter, unlike the other leakages, depend not only upon the magnetic dimensions, number of turns, etc., of the motor, but also varies largely with the secondary resistance. The belt leakage phenomena depend upon the current distribution of the secondary, and the secondary current distribution in turn changes with the secondary resistance. It may be shown, for instance, that in a squirrel-cage secondary with a resistance of zero, the current distribution is not even approximately sinusoidal but approaches closely to that of the primary, the secondary being assumed stationary. In this case the counter magnetomotive forces of the secondary are, at all parts of the circumference, equal and opposite to those of the primary. Therefore the belt leakage fluxes cannot exist. Assuming the other extreme; that is, a secondary of very high resistance, the current distribution in the secondary will be approximately sinusoidal, and the secondary magnetomotive forces are no longer distributed like those of the primary. A certain differential action; that is, belt leakage fluxes, seems therefore to be possible in this case at certain parts of the circumference. It will be of little value to discuss these questions more in detail at this time since I have not yet arrived at definite conclusions as to their practical importance.

*A paper presented at the 25th annual convention of the American Institute of Electrical Engineers, Atlantic City, N. J., July 2, 1908.*

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# A TRIGONOMETRIC METHOD FOR THE SOLUTION OF ALTERNATING CURRENT PROBLEMS

BY HAROLD PENDER

In a single-phase alternating-current circuit, the ratio of the mean effective pressure $E$ to the mean effective current $I$, is defined as the impedance $z$ of the circuit; that is,

$$z = \frac{E}{I}$$

The power absorbed in the circuit is

$$W = r\,I^2$$

where $r$ is the effective resistance of the circuit.

If $L$ is the coefficient of self-induction of the circuit and $\sim$ the frequency, then the relation between the resistance and impedance of a circuit is

$$z = \sqrt{r^2 + x^2}$$

where $x$, called the reactance of the circuit, equals $2\,\pi \sim L$.

For two or more circuits *in series*, the resistances and reactances are additive, respectively; the resultant impedance is therefore

$$z = \sqrt{(r_1 + r_2 + \ .\ .\ .\ )^2 + (x_1 + x + \ .\ .\ .\ )^2}$$

In the case of two or more circuits *in parallel*, the quantities

Admittance $\qquad y = \frac{I}{E} = \frac{1}{z}$

Conductance $\qquad g = \frac{W}{E^2} = \frac{r}{r^2 + x^2}$

Susceptance $b = \sqrt{y^2 - g^2} = \dfrac{x}{r^2+x^2}$

lend themselves more readily to mathematical analysis, since conductances and susceptances are respectively additive; the resultant admittance is therefore

$$y = \sqrt{(g_1+g_2+\ .\ .\ .\ )+(b_1+b_2+\ .\ .\ .\ )^2}$$

These complex forms for impedance and admittance render the formulas for most alternating-current problems exceedingly complicated, and numerical calculations become extremely tedious after the first or second operation.

The following method of treating such problems will be found much simpler. The fundamental idea involved is the use of certain factors; namely, the ratio of the reactance to the resistance, the "reactance-factor" $t$, and the ratio of the resistance to the impedance, the "power-factor" $k$, instead of employing the reactance and impedance directly. From the triangle giving the relation between resistance, reactance, and impedance,

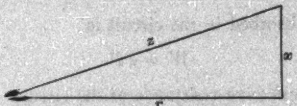

FIG. 1

it is evident that the reactance-factor $t\left(=\dfrac{x}{r}\right)$ and the power-factor $k\left(=\dfrac{r}{z}\right)$ are the tangent and cosine, respectively, of the same angle. If either of the two quantities $t$ or $k$ is known, the other can then be taken directly from a table of cosines and tangents. Table I, giving the values of $t$ (tangent) in terms of $k$ (cosine) is arranged in a form more convenient than the usual trigonometric tables. Of the two factors, $k$ is the more readily determined from actual measurements, since

$$k = \frac{W}{E\,I}$$

$t$ can then be taken from the table. If the reactance $x$ and resistance $r$ of the circuit are known, $t$ can be readily calculated, since

$$t = \frac{x}{r}$$

$k$ can then be taken from the table.

Below will be found the solution of a number of alternating-current problems by this new method. A comparison of the formulas deduced with those ordinarily used will make evident at once the simplicity of this method, especially for numerical calculations.

The ordinary quantities, reactance, impedance, conductance, susceptance, and admittance can all be expressed by simple formulas in terms of resistance and the trigonometric quantities $t$ and $k$, namely:

Resistance $$r = r \qquad (1)$$

Reactance $$x = r\,t \qquad (2)$$

Impedance $$z = \frac{r}{k} \qquad (3)$$

Conductance $$g = \frac{k^2}{r} \qquad (4)$$

Susceptance $$b = g\,t \qquad (5)$$

Admittance $$y = \frac{g}{k} \qquad (6)$$

The relations between current, pressure, and power absorbed in the circuit, are

Current $$I = \frac{k\,E}{r} = \frac{g\,E}{k} = \frac{W}{k\,E} \qquad (7)$$

Pressure $$E = \frac{k\,I}{g} = \frac{r\,I}{k} = \frac{W}{k\,I} \qquad (8)$$

Resistance and conductance may likewise be expressed in terms of current, pressure, and power; namely,

$$r = \frac{W}{I^2} = \frac{(k\,E)^2}{W} \qquad (9)$$

$$g = \frac{W}{E^2} = \frac{(k\,I)^2}{W} \qquad (10)$$

When $r = 0$, then $g = 0$, and $k = 0$, and the expressions for $I$ and $E$ reduce to the following forms:

Current $$I = bE = \frac{E}{x} \qquad (7a)$$

Pressure $$E = xI = \frac{I}{b} \qquad (8a)$$

The power absorbed in the circuit is, of course, zero.

*Reactance-factor of two or more circuits in series.* Since resistances and reactances are respectively additive, the combined resistance of two or more circuits is

$$R^* = r_1 + r_2 + \ldots \qquad (11)$$

and the combined reactance is

$$X = x_1 + x_2 + \ldots \qquad (12)$$

Hence the reactance-factor of two or more circuits in series is

$$T = \frac{X}{R} = \frac{x_1 + x_2 + \ldots}{r_1 + r_2 + \ldots} \qquad (13)$$

or

$$T = \frac{r_1 t_1 + r_2 t_2 + \ldots}{R} \qquad (13a)$$

The resultant reactance-factor has the form of a weighted average, the " weight " being the corresponding resistance.

*Reactance-factor of two or more circuits in parallel.* Since conductances and susceptances are respectively additive, the combined conductance of two or more circuits is

$$G = g_1 + g_2 + \ldots \qquad (14)$$

and the combined susceptance is

$$B = b_1 + b_2 + \ldots \qquad (15)$$

and the reactance-factor of the combined circuits is

$$T = \frac{B}{G} = \frac{b_1 + b_2 + \ldots}{g_1 + g_2 + \ldots} \qquad (16)$$

or

$$T = \frac{g_1 t_1 + g_2 t_2 + \ldots}{G} \qquad (16a)$$

---

* Throughout this paper lower-case italic letters will be used for constants of a simple circuit, capitals for the constants of combined circuits.

As in the case of two or more circuits in series the reactance-factor of the combined circuits is a weighted average, the weights for parallel circuits being the corresponding conductances.

## SIMPLE TRANSMISSION CIRCUIT

*Single-phase line.* Consider a load of $W$ watts, of power-factor $k$, supplied at a pressure $E$ over a line of resistance $r_1$ ohms and reactance factor $t_1$. (Table II gives the values of the reactance factor for various sizes of wires spaced various distances apart.)

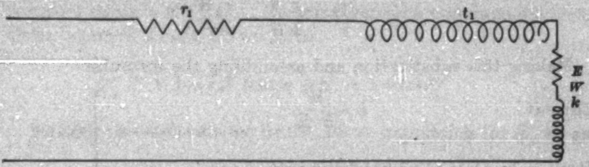

FIG. 2

Given the above constants, to find

$I$ = current, in amperes
$E_0$ = pressure at generator end, in volts
$K_0$ = power-factor at generator end
$W_0$ = power supplied at generator end, in watts.

From equation (7)

$$I = \frac{W}{k\,E}$$

From equation (9), the effective resistance of the receiver is

$$r = \frac{(k\,E)^2}{W}$$

From Table I take the reactance-factor $t$, corresponding to $k$.

From equation (13a) the reactance-factor at the generator end is

$$T_0 = \frac{r\,t + r_1\,t_1}{r + r_1}$$

whence $K_0$, the power-factor at the generator end, is taken directly from Table I.

From equations (8) and (7) the pressure at the generator end is

$$E_0 = \frac{r+r_1}{K_0} I = \frac{r+r_1}{r} \quad \frac{k}{K_0} E$$

From equation (9) the power supplied at the generator end is

$$W_0 = (r+r_1) I^2 = \frac{r+r_1}{r} W$$

These formulas can be somewhat simplified by introducing the ratio of power lost in line to power delivered, which can be epresented by $Q$, and has the value

$$Q = \frac{r_1}{r} = \frac{r_1 I}{k E} = \frac{r_1 W}{(k E)^2}$$

Making this substitution and assembling the formulas

Current $I = \dfrac{W}{k\,E}$

Ratio power lost to power delivered

$$Q = \frac{r_1 I}{k E}$$

Power supplied at generator end

$$W_0 = (1+Q)\, W$$

Reactance-factor at generator end

$$T_0 = \frac{t + t_1 Q}{1+Q}$$

Power-factor at generator end,

$K_0$ corresponding to $T_0$ from Table I

Ratio of pressure drop to pressure delivered

$$D = \frac{k}{K_0}(1+Q) - 1$$

Pressure at generator end

$$E_0 = (1+D)\, E$$

17

*Three-phase line.* The formulas just deduced also hold for a three-phase line except that $I$, the line current, is

$$I = \frac{W}{\sqrt{3}\, k\, E}$$

and the resistance $r_1$ is the resistance of *each leg* of the line.

The formula for generator pressure $E_0$ can be put in a form not involving the calculation of the power-factor $K_0$, which form also leads to a very simple approximate expression for the pressure-drop in the line. Remembering the trigonometric relations between $T$ and $K$, we have

$$\frac{1}{K_0} = \sqrt{1+T_0^2} \text{ (since } \sec^2 = 1+\tan^2\text{)}$$

Making this substitution in the above expression for $E_0$ we get

$$E_0 = E\sqrt{1+2\,(1+t_1\, t)\, k^2\, Q+\left(\frac{k}{k_1}\, Q\right)^2}$$

Expanding this radical in the form of an infinite series and neglecting the terms of the second or higher order in $Q$, we have as a first approximation, for ordinary practical cases where the power lost in the line is 20 per cent. or less and the reactance of the line of the same order of magnitude as the resistance,

$$E_0 = E\,[1+(1+t_1\, t)\, k^2\, Q]$$

or putting

$$M = (1+t_1\, t) k^2$$

$$E_0 = (1+M\, Q)\, E$$

The ratio of pressure lost in the line to pressure at receiver is then

$$D = M\, Q^*$$

$M$ may be called the " drop-factor ", it depends only on the reactance-factors of the line and the load.

The power-factor at the generator is

$$K_0 = \frac{W_0}{E_0\, I} = \frac{1+Q}{1+D}\, k$$

---

* For a geometric proof of this formula see an article by the author in the *Elec. World*, Vol. 46, p. 18, 1905.

We have then for the three characteristics of a transmission line the simple formulas

$$\left.\begin{array}{ll}\text{Ratio of power lost to power delivered} & Q=\dfrac{r_1 W}{(k E)^2}\\[2ex] \text{Ratio of pressure lost to pressure delivered} & D=M\,Q\\[2ex] \text{Power factor at generator end} & K_0=\dfrac{1+Q}{1+D}\,k\end{array}\right\}\quad(18)$$

The expressions for $D$ and $K_0$ are approximate, but for most practical cases are sufficiently accurate. Table III gives the values of $M$ for various load power-factors and line reactance-factors. The degree of approximation involved in the use of this table is also indicated; note that an error of five per cent., for example, in a pressure drop of ten per cent. produces an error of only 0.5 per cent. in the absolute value of the pressure.

Should one wish to determine the drop with absolute accuracy, or should $M$ fall below the limits indicated by the letters in the table, the exact formulas 17, or the radical expression

$$D=\sqrt{1+2\,M\,Q+\left(\frac{k}{k_1}\,Q\right)^2}-1$$

should be used.

*Three-phase line.* These formulas also hold for a three-phase line when $r_1$ represents the resistance of *each leg* of the line.

*Numerical examples.* A load of 5000 kw. is to be delivered at 30,000 volts to a receiver having a 95 per cent. power-factor over a 40-mile single-phase line of No. 00 copper wire; frequency 25 cycles, wires 4 ft. apart.

From Table II, the resistance of the line is

$$r = 2\times 40\times 0.411 = 32.9$$

and the reactance-factor

$$t_1 = \frac{2.87}{4} = 0.717$$

Applying the exact formulas (17):

Current $$I=\frac{5\times 10^6}{0.95\times 3\times 10^4}=175.6 \text{ amperes.}$$

Ratio of power lost to power delivered

$$Q=\frac{32.9\times 175.6}{0.95\times 3\times 10^4}=0.203$$

Power supplied at generator end

$$W_0 = 1.203 \times 5000 = 6020 \text{ kw.}$$

Reactance-factor at generator end

$$T_0 = \frac{0.329 + 0.717 \times 0.203}{1.203} = 0.394$$

Power-factor at generator end $K_0 = 0.930$

Ratio of pressure drop to pressure delivered

$$D = \frac{0.95}{0.93} \times 1.203 - 1 = 0.230$$

Pressure at generator end $E_0 = 1.230 \times 30{,}000 = 36{,}900$ volts.

Applying the approximate formulas (18)
Ratio of power loss to power delivered

$$Q = \frac{32.9 \times 5 \times 10^6}{(0.95 \times 3 \times 10^4)^2} = 0.203$$

Drop-factor $M = 1.14$ from Table III.

Ratio of pressure drop to pressure delivered

$$D = 1.14 \times 0.203 = 0.232$$

Power-factor at generator end

$$K_0 = \frac{1.203}{1.232} \times 0.95 = 0.928$$

The value for $D$ is 1 per cent. high, and the value for $K_0$ 0.2 per cent. low.

Consider the same load supplied over a *three-phase line* of the same length; the power-factor, frequency, size, and spacing of the wires remaining the same.

In this case
Resistance of each leg $r_1 = 40 \times 0.411 = 16.4$

Reactance-factor $t_1 = \frac{2.87}{4} = 0.717$

Applying the exact formulas (17)

Current $I = \frac{5 \times 10^6}{\sqrt{3}.95 \times 3 \times 10^4} = 101.5$ amperes.

Ratio of power lost to power delivered

$$Q=\frac{16.4\times 5\times 10^6}{(0.95\times 3\times 10^4)^2}=0.101$$

Power supplied at generator end

$$W_0=1.101\times 5000=5505 \text{ kw.}$$

Reactance-factor at generator end

$$T_0=\frac{0.329+0.717\times 0.101}{1.101}=0.364$$

Power-factor at generator end

$$K_0=0.940$$

Ratio of pressure drop to pressure delivered

$$D=1-\frac{0.95}{0.94}\times 1.101=0.113$$

Pressure at generator end $E_0=1.113\times 30{,}000=33{,}600$ volts

Applying the approximate formula (18)

$$Q=\frac{16.4\times 5\times 10^6}{(0.95\times 3\times 10^4)^2}=0.101$$

$$M=1.14$$

Ratio of pressure drop to pressure delivered

$$D=1.14\times 0.101=0.115$$

Power-factor at generator end

$$K_0=\frac{1.101}{1.115}\times 0.95=0.938$$

## THE CAPACITY EFFECT IN A TRANSMISSION LINE

The capacity effect in a transmission line can be calculated with sufficient accuracy in most practical cases by considering a condenser of one-half the capacity of the line shunted across the line at each end, or as shown diagrammatically, where, in case of a *single-phase line*

$r_1$ = resistance of both wires in ohms

$t_1$ = reactance factor of the line

$b$ = one half the capacity susceptance of the line (see Table IV)
$E$ = pressure between wires at receiver in volts
$W$ = power delivered in watts
$k$ = power-factor of the load

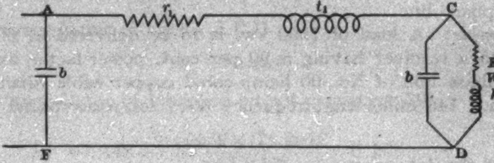

FIG. 3

Then,
Conductance of the receiver (equation 10)

$$g = \frac{W}{E^2}$$

Reactance-factor of receiver: $t$ corresponding to $k$
Reactance factor of the load and the condenser in parallel at receiver end (equation 16a)

$$T_1 = \frac{g\,t + b}{g}$$

whence from equation (10)

$$T_1 = t + \frac{b\,E^2}{W} \tag{19}$$

Power factor of the load and the condenser in parallel at receiver end is then: $K_1$ corresponding to $T_1$

When $K_1$ has been found, the power loss, regulation, and power factor of the circuit A C D can be determined either by the exact formulas 17 or the approximate formula 18. The power loss and regulation of the complete circuit A C D F is the same as for the circuit A C D; the power-factor of the circuit A C D F, that is, the power-factor at the generator end, is the power-factor corresponding to the reactance factor of the complete circuit, *i. e.*,

$$T_2' = T_2 + \frac{b\,E_0^2}{W_2} \tag{20}$$

where $T_2$ is the reactance-factor of the circuit A C D.

*Three-phase line.* The above equations also hold for a three-phase line when

$r_1$ = resistance of each wire in ohms
$b$ = capacity susceptance of each pair of wires

the other symbols having the same meaning as in the case of a single-phase line.

*Example*: A load of 7500 kw. is to be delivered at 60,000 volts to a receiver having a 90 per cent. power-factor over a three-phase line of No. 00 hemp-cored copper cable (diameter 0.45 in.), 140 miles long; frequency 60 cycles, wires spaced 8 ft. apart.

From the data given:

Resistance of each wire in ohms, $r_1 = 140 \times 0.411 = 57.5$ (Table II)
Reactance-factor $t_1 = 0.6 \times 3.2 = 1.92$ (Table II)
Capacity susceptance of each pair of wires

$b = -0.6 \times 4.64 \times 10^{-6} \times 140 = -0.00039$ (Table IV)

Pressure between wires at receiver $E = 6 \times 10^4$
Power delivered $W = 7.5 \times 10^6$
Power-factor of load $k = 0.9$

Then from equation 19,

$$T_1 = 0.484 - \frac{0.00039 \times (6 \times 10^4)^2}{7.5 \times 10^6} = 0.297$$

Using the approximate formula 18,

$$K_1 = 0.959$$

Ratio of power lost to power delivered

$$Q = \frac{57.5 \times 7.5 \times 10^6}{(0.959 \times 6 \times 10^4)^2} = 0.130$$

Drop-factor, $M_1 = (1 + 1.92 \times 0.297)\ (0.959)^2 = 1.44$

Ratio of pressure lost to pressure delivered

$$D = 1.44 \times 0.130 = 0.187$$

Total power supplied by generator

$$W_0 = 1.13 \times 7{,}500 = 8{,}470 \text{ kw.}$$

Pressure at generator $E_0 = 1.187\times 60{,}000 = 71{,}200$ volts

Power-factor of circuit A C D

$$K_0 = \frac{1.13}{1.187}\times 0.959 = 0.913$$

Reactance-factor of circuit A C D

$$T_0 = 0.448$$

Reactance-factor of complete circuit (equation 20)

$$T_0' = 0.448 - \frac{0.00039\times (71{,}200)^2}{8.47\times 10^6} = 0.204$$

Power-factor of complete circuit A C D F

$$K_0 = 0.98$$

## THE ALTERNATING-CURRENT TRANSFORMER

In treating the transformer it is simpler to reduce all the constants of the secondary to equivalent primary values; that is, to consider a transformer having a one-to-one ratio. If the actual ratio of the primary turns to secondary turns is $a$, then the true secondary resistance and reactance are each multiplied by $a^2$, the true secondary electromotive force is multiplied by $a$, and the true secondary current divided by $a$. The transformer may then be represented diagrammatically as shown where

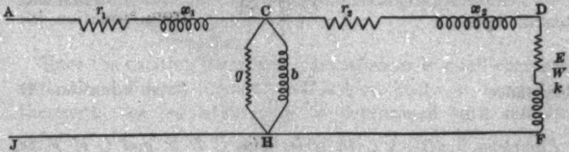

FIG. 4

$r_1$ = primary resistance in ohms
$x_1$ = primary reactance in ohms
$r_2$ = secondary resistance, reduced to primary, in ohms
$x_2$ = secondary reactance, reduced to primary, in ohms
$g$ = primary exciting conductance
$b$ = primary exciting susceptance

$E$ = secondary terminal electromotive force, reduced to primary
$W$ = external load on secondary
$k$ = power-factor of the external load

The following is the complete solution:

*Receiver-circuit D F*

| | | |
|---|---|---|
| Resistance | $r = \frac{(kE)^2}{W}$ | (from equation 9) |
| Reactance-factor | $t$ corresponding to $k$ | |

*Receiver in series with secondary-circuit C D F*

| | | |
|---|---|---|
| Resistance | $R_2 = r + r_2$ | (from equation 11) |
| Reactance-factor | $T_2 = \frac{r\,t + x_2}{R_2}$ | (from equation 13) |
| Conductance | $G_2 = \frac{K^2_2}{R_2}$ | (from equation 4) |

*Receiver in series with secondary shunted by exciting circuit—circuits C D F and C H F in parallel.*

| | | |
|---|---|---|
| Conductance | $G = G_2 + g$ | (from equation 14) |
| Reactance-factor | $T = \frac{G_2\,T_2 + b}{G}$ | (from equation 16) |
| Resistance | $R = \frac{K^2}{G}$ | (from equation 4) |

*Complete-circuit—A C in series with C D F and C H F in parallel*

| | | |
|---|---|---|
| Resistance | $R_1 = R + r_1$ | (from equation 11) |
| Reactance-factor | $T_1 = \frac{R\,T + x_1}{R_1}$ | (from equation 13) |
| Then power-factor | $K_1$ corresponding to $T_1$ | |
| Receiver current | $I_2 = \frac{W}{k\,E}$ | (from equation 7) |

Induced electromotive force (pressure across D F)

$$E' = \frac{R_2 I_2}{K_2} \qquad \text{(from equation 8)}$$

Magnetizing current $I_m' = b\,E'$ (from equation 7a)

Total exciting current $I' = \frac{g\,E'}{k'}$ (from equation 7)

where $k'$ corresponds to the reactance factor $t' = \frac{b}{g}$

Total primary current $I_1 = \frac{G\,E'}{K}$ (from equation [illegible])

Primary impressed electromotive force

$$E_1 = \frac{R_1 I_1}{K_1} \qquad \text{(from equation 8)}$$

Total power input $W_1 = R_1 I_1^2$ (from equation 9)

Power factor of total input is $K_1$ corresponding to $T_1$

Efficiency $e = \frac{W_2}{W_1}$

Since the exciting current of a transformer is small compared with the full-load current, and is practically in quadrature therewith, the regulation may be determined with sufficient accuracy by neglecting the exciting current altogether, in which case the transformer diagram reduces to that of the simple transmission line, and equations (17) or (18) are directly applicable.

*Example.* Given a transformer of the following constants

| | |
|---|---|
| Ratio of primary to secondary turns | $a = 10$ |
| Primary resistance | $r' = 5$ |
| Primary reactance | $x' = 11$ |
| Actual secondary resistance | $r'' = 0.04$ |
| Actual secondary reactance | $x'' = 0.09$ |

Exciting current negligible.

To find regulation $D$ when the secondary is supplying 5000 kw. at 10,000 volts to a receiver of 85 per cent. power-factor.

Total equivalent resistance $r_0 = r' + a^2 r'' = 5 + 100 \times .04 = 9$
Total equivalent reactance $x_0 = x' + a^2 x'' = 11 + 100 \times .09 = 20$

Equivalent reactance factor $t_0 = \dfrac{20}{9} = 2.22$

Applying equations (18)

Ratio of copper loss to power delivered

$$Q = \frac{9 \times 5 \times 10^6}{(0.85 \times 6 \times 10^4)^2} = 0.0173$$

Drop-factor $M = 1.71$ (from Table II)

Regulation $D = 1.71 \times 0.0173 = 0.0296$

The total power loss in the transformer is $Q\,W +$ the core loss.

The equivalent resistance and reactance factor of a transformer is readily obtained from the short circuit test.

Let

$I_0$ = primary current when secondary is short circuited

$E_0$ = primary applied pressure when secondary is short circuited, small compared to normal pressure

$W_0$ = input in watts

Then

Equivalent resistance $r_0 = \dfrac{W_0}{I^2_0}$

Power-factor $k_0 = \dfrac{W_0}{E_0 I_0}$

Reactance-factor $t_0$ corresponding to $k_0$

### Transformer in Series with a Transmission Line

A transmission line and transformer in series reduce to a simple transmission circuit having a resistance equal to the sum of the line and transformer resistances and a reactance equal to the sum of the line and transformer reactances. The effect of the exciting current on the copper loss and pressure drop may be neglected. In figuring the total efficiency the core loss of the transformer must of course be included.

### THE INDUCTION MOTOR

The current taken by an induction motor running at slip $s$ is the same as the motor would take if the secondary were locked and the secondary resistance increased from $r_2$ to $r_2/s$ and the secondary reactance increased from $s\,x_2$ to $x_2$ respectively; in other words the performance of an induction motor is the same as that of a transformer with a variable resistance in the secondary. Diagrammatically each phase of the motor may be represented as shown:

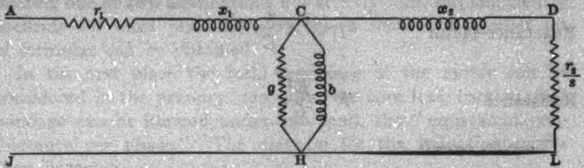

FIG. 5

where $r_1$ = primary resistance per phase

$x_1$ = primary reactance per phase

$r_2$ = secondary resistance per phase reduced to the primary.

$x_2$ = secondary reactance per phase reduced to the primary.

$g$ = exciting admittance per phase

$b$ = exciting susceptance per phase

$s$ = slip

$F$ = total loss in windage and friction at synchronous speed

$(1-s)F$ = total loss in friction and windage when speed = $n\,(1-s)$

$E$ = impressed volts per phase (equals volts between terminals for a delta connected primary; for star connected primary equals volts between terminals divided by $\sqrt{3}$)

Also let

$q$ = number of phases

$n$ = synchronous speed in revolutions per minute

Then *for the secondary circuit C D L*

Resistance $R_2 = \frac{r_2}{s}$

Reactance-factor $T_2 = \frac{x_2}{R_2}$

Conductance $G_2 = \frac{K_2^2}{R_2}$

*Secondary in parallel with exciting circuit, circuits* $<\genfrac{}{}{0pt}{}{\text{CDLH}}{\text{CH}}>$

Conductance $G = G_2 + g$

Reactance-factor $T = \frac{G_2\, T_2 + b}{G}$

Resistance $R = \frac{K^2}{G}$

*Complete circuit*

Resistance $R_1 = R + r_1$

Reactance-factor $T_1 = \frac{R\, T + x_1}{R_1}$

Then

Primary current $I_1 = \frac{K_1\, E}{R_1}$

Induced electromotive force

$$E' = \frac{K\, I_1}{G}$$

Exciting current $I' = \frac{g\, E'}{k'}$

where $k'$ corresponds to $t' = \frac{b}{g}$

Secondary current $I_2 = \frac{G_2\, E'}{K_2}$

Total watts supplied to primary $W_1 = q\, R_1\, I_1^2$
Total watts supplied to secondary $W_2' = q\, R_2\, I_2^2$
Watts lost in true secondary resistance $= q\, r_2\, I_2^2$
Mechanical output of motor $W_2 = (1-s)\,[q\, R_2\, I_2^2 - F]$

Torque in pounds at one-foot radius

$$T = \frac{7.04\ W_2}{n(1-s)}$$

Efficiency $e = \frac{W_2}{W_1}$

Power-factor $K_1$ corresponding to $T_1$

This is the complete solution of the induction motor, but by making one or two assumptions not strictly true, but sufficiently accurate for most practical purposes, a somewhat simpler set of formulas can be obtained

In the first place the total reactance of the motor can be considered in the primary; secondly, the core loss, friction, and windage can be lumped under one head, the "equivalent conductance per phase." The diagram for the induction motor then becomes,

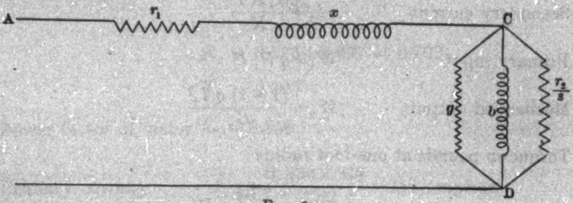

FIG. 6

where $r_1$ = primary resistance per phase
$x$ = total reactance (primary and secondary) per phase
$r_2$ = secondary resistance per phase
$g$ = equivalent exciting conductance per phase
$b$ = exciting susceptance per phase
$s$ = slip
$E$ = impressed volts per phase (equals volts between terminals for a delta connected primary; for a star connected primary equals volts between terminals divided by $\sqrt{3}$)

Then equivalent conductance of secondary

$$G_2 = \frac{s}{r_2}$$

*For the multiple circuit C D*

Conductance $G = G_2 + g$

Reactance-factor $T = \dfrac{b}{G}$

Resistance $R = \dfrac{K^2}{G}$

*Complete circuit A C D*

Resistance $R_1 = R + r_1$

Reactance-factor $T_1 = \dfrac{R\ T + x}{R_1}$

Then

Primary current $I_1 = \dfrac{K_1\ E_1}{R_1}$

Secondary current $I_2 = \dfrac{G_2\ R\ I}{K}$

Primary input $W_1 = q\ R_1\ I^2$

Mechanical output $W_2 = \dfrac{(1-s)\ q\ I_2^2}{G_2}$

Torque in pounds at one-foot radius

$$T = \frac{7.04}{n\ (1-s)}\ W_2$$

Efficiency $e = \dfrac{W_2}{W_1}$

Power-factor $K_1$ corresponding to $T$.

*Example.* Given a three-phase induction motor star-connected, 550 volts between terminals, 375 rev. per min., having the following constants

| | | |
|---|---|---|
| Primary resistance per phase | $r_1 = 0.027$ | ohms |
| Total reactance per phase | $x = 0.25$ | " |
| Secondary resistance per phase | $r_2 = 0.022$ | " |
| Equivalent exciting conductance per phase | $g = 0.024$ | " |
| Exciting susceptance per phase | $b = 0.36$ | " |
| Revolutions per minute | $n = 375$ | " |

What will be the performance of the motor when the slip $s = 0.03$?

Since the primary is star connected

$$E = \frac{550}{\sqrt{3}} = 318$$

Substituting these values in the formulas just deduced

$$G_2 = \frac{0.03}{0.022} = 1.364$$

$$G = 1.364 + 0.024 = 1.388$$

$$T = \frac{0.36}{1.388} = 0.259$$

$$K = 0.968$$

$$R = \frac{(0.968)^2}{1.388} = 0.675$$

$$R_1 = 0.675 + 0.027 = 0.702$$

$$T_1 = 0.605$$

Power factor of motor $K_1 = 0.856$

Primary current $I_1 = \dfrac{0.856 \times 318}{.702} = 388$ amperes

Secondary current $I_2 = \dfrac{1.364 \times 0.675 \times 338}{0.968} = 369$ amperes

Primary input $W_1 = 3 \times 0.702 \times 388^2 = 316$ kw.

Mechanical output $W_2 = \dfrac{0.97 \times 3 \times 369^2}{1.364} = 291$ kw.

Torque $T = \dfrac{7.04 \times 291000}{375 \times 0.97} = 5630$ lb.

Efficiency $e = \dfrac{291}{316} = 0.921$

The constants of an induction motor are easily determined from the free running and locked tests.

Let

$E'$ = primary impressed volts per phase when running light
$W'$ = watts input per phase when running light
$I'$ = current per phase, when running light
$E_0$ = primary impressed volts per phase, rotor locked
$W_0$ = watts input per phase, rotor locked
$I_0$ = current input per phase, rotor locked
Primary resistance per phase $r_1$ measured by means of direct current

Then

Secondary resistance per phase $r_2 = \frac{W_0}{I_0^2} - r.$

Power-factor locked $k_0 = \frac{W_0}{E_0 I_0}$

Total reactance per phase $x = (r_1 + r_2)\ t_0$
where $t_0$ corresponds to $k_0$

Equivalent exciting conductance per phase $g' = \frac{W'}{E'^2}$

Power-factor, running light $k' = \frac{W'}{E' I'}$

Exciting susceptance per phase $b' = g'\ t'$
where $t'$ corresponds to $k'$

## TABLE 1.

### VALUES OF *t* (= tan) IN TERMS OF *k* (= cos).

| *K* | 0.000 | 0.002 | 0.004 | 0.006 | 0.008 | *K* | 0.000 | 0.002 | 0.004 | 0.006 | 0.008 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 |  | 500 | 250 | 167 | 125 | 0.50 | 1.732 | 1.723 | 1.714 | 1.705 | 1.696 |
| 0.01 | 100 | 83.3 | 71.4 | 62.5 | 55.5 | 0.51 | 1.687 | 1.678 | 1.669 | 1.660 | 1.651 |
| 0.02 | 50.0 | 45.4 | 41.6 | 38.4 | 35.7 | 0.52 | 1.643 | 1.634 | 1.626 | 1.617 | 1.608 |
| 0.03 | 33.3 | 31.2 | 29.4 | 27.7 | 26.3 | 0.53 | 1.600 | 1.592 | 1.583 | 1.575 | 1.567 |
| 0.04 | 25.0 | 23.8 | 22.7 | 21.7 | 20.8 | 0.54 | 1.559 | 1.550 | 1.542 | 1.534 | 1.526 |
| 0.05 | 20.0 | 19.2 | 18.5 | 17.8 | 17.2 | 0.55 | 1.519 | 1.511 | 1.503 | 1.495 | 1.487 |
| 0.06 | 16.6 | 16.1 | 15.6 | 15.1 | 14.7 | 0.56 | 1.479 | 1.471 | 1.464 | 1.457 | 1.449 |
| 0.07 | 14.3 | 13.8 | 13.5 | 13.1 | 12.8 | 0.57 | 1.442 | 1.434 | 1.427 | 1.419 | 1.412 |
| 0.08 | 12.5 | 12.2 | 11.9 | 11.6 | 11.3 | 0.58 | 1.404 | 1.397 | 1.390 | 1.383 | 1.376 |
| 0.09 | 11.1 | 10.8 | 10.6 | 10.4 | 10.2 | 0.59 | 1.368 | 1.361 | 1.354 | 1.347 | 1.340 |
| 0.10 | 9.95 | 9.75 | 9.56 | 9.38 | 9.21 | 0.60 | 1.333 | 1.326 | 1.319 | 1.313 | 1.306 |
| 0.11 | 9.03 | 8.87 | 8.71 | 8.56 | 8.41 | 0.61 | 1.299 | 1.292 | 1.286 | 1.279 | 1.272 |
| 0.12 | 8.27 | 8.14 | 8.00 | 7.87 | 7.75 | 0.62 | 1.265 | 1.259 | 1.252 | 1.246 | 1.239 |
| 0.13 | 7.63 | 7.51 | 7.40 | 7.28 | 7.18 | 0.63 | 1.233 | 1.226 | 1.220 | 1.213 | 1.207 |
| 0.14 | 7.07 | 6.97 | 6.87 | 6.78 | 6.68 | 0.64 | 1.201 | 1.194 | 1.188 | 1.181 | 1.175 |
| 0.15 | 6.59 | 6.50 | 6.42 | 6.33 | 6.25 | 0.65 | 1.169 | 1.163 | 1.157 | 1.151 | 1.144 |
| 0.16 | 6.17 | 6.09 | 6.02 | 5.94 | 5.87 | 0.66 | 1.138 | 1.132 | 1.126 | 1.120 | 1.114 |
| 0.17 | 5.80 | 5.73 | 5.66 | 5.59 | 5.53 | 0.67 | 1.108 | 1.102 | 1.096 | 1.090 | 1.084 |
| 0.18 | 5.47 | 5.40 | 5.34 | 5.28 | 5.22 | 0.68 | 1.078 | 1.072 | 1.067 | 1.061 | 1.055 |
| 0.19 | 5.17 | 5.11 | 5.06 | 5.00 | 4.95 | 0.69 | 1.049 | 1.043 | 1.037 | 1.032 | 1.026 |
| 0.20 | 4.90 | 4.85 | 4.80 | 4.75 | 4.70 | 0.70 | 1.020 | 1.015 | 1.009 | 1.003 | 0.997 |
| 0.21 | 4.66 | 4.61 | 4.56 | 4.52 | 4.48 | 0.71 | 0.992 | 0.986 | 0.981 | 0.975 | 0.969 |
| 0.22 | 4.43 | 4.39 | 4.35 | 4.31 | 4.27 | 0.72 | 0.964 | 0.968 | 0.953 | 0.947 | 0.942 |
| 0.23 | 4.23 | 4.19 | 4.15 | 4.12 | 4.08 | 0.73 | 0.936 | 0.931 | 0.925 | 0.920 | 0.914 |
| 0.24 | 4.05 | 4.01 | 3.97 | 3.94 | 3.91 | 0.74 | 0.909 | 0.904 | 0.898 | 0.893 | 0.887 |
| 0.25 | 3.87 | 3.84 | 3.81 | 3.78 | 3.75 | 0.75 | 0.882 | 0.877 | 0.871 | 0.866 | 0.860 |
| 0.26 | 3.71 | 3.68 | 3.65 | 3.62 | 3.59 | 0.76 | 0.855 | 0.850 | 0.845 | 0.839 | 0.834 |
| 0.27 | 3.57 | 3.54 | 3.51 | 3.48 | 3.46 | 0.77 | 0.829 | 0.823 | 0.818 | 0.813 | 0.808 |
| 0.28 | 3.43 | 3.40 | 3.38 | 3.35 | 3.33 | 0.78 | 0.802 | 0.797 | 0.792 | 0.787 | 0.781 |
| 0.29 | 3.30 | 3.28 | 3.25 | 3.23 | 3.20 | 0.79 | 0.776 | 0.771 | 0.766 | 0.760 | 0.755 |
| 0.30 | 3.18 | 3.16 | 3.13 | 3.11 | 3.09 | 0.80 | 0.750 | 0.745 | 0.740 | 0.734 | 0.729 |
| 0.31 | 3.07 | 3.05 | 3.02 | 3.00 | 2.98 | 0.81 | 0.724 | 0.719 | 0.714 | 0.708 | 0.703 |
| 0.32 | 2.96 | 2.94 | 2.92 | 2.90 | 2.88 | 0.82 | 0.698 | 0.693 | 0.688 | 0.682 | 0.677 |
| 0.33 | 2.86 | 2.84 | 2.82 | 2.80 | 2.78 | 0.83 | 0.672 | 0.667 | 0.662 | 0.656 | 0.651 |
| 0.34 | 2.77 | 2.75 | 2.73 | 2.71 | 2.69 | 0.84 | 0.646 | 0.641 | 0.635 | 0.630 | 0.625 |
| 0.35 | 2.68 | 2.66 | 2.64 | 2.63 | 2.61 | 0.85 | 0.620 | 0.614 | 0.609 | 0.604 | 0.599 |
| 0.36 | 2.59 | 2.58 | 2.56 | 2.54 | 2.53 | 0.86 | 0.593 | 0.588 | 0.583 | 0.577 | 0.572 |
| 0.37 | 2.51 | 2.50 | 2.48 | 2.46 | 2.45 | 0.87 | 0.567 | 0.561 | 0.556 | 0.551 | 0.545 |
| 0.38 | 2.43 | 2.42 | 2.40 | 2.39 | 2.38 | 0.88 | 0.540 | 0.534 | 0.529 | 0.523 | 0.518 |
| 0.39 | 2.36 | 2.35 | 2.33 | 2.32 | 2.30 | 0.89 | 0.512 | 0.507 | 0.501 | 0.496 | 0.490 |
| 0.40 | 2.29 | 2.28 | 2.26 | 2.25 | 2.24 | 0.90 | 0.489 | 0.479 | 0.473 | 0.467 | 0.461 |
| 0.41 | 2.22 | 2.21 | 2.20 | 2.19 | 2.17 | 0.91 | 0.456 | 0.450 | 0.444 | 0.438 | 0.432 |
| 0.42 | 2.16 | 2.15 | 2.14 | 2.12 | 2.11 | 0.92 | 0.426 | 0.420 | 0.414 | 0.408 | 0.401 |
| 0.43 | 2.10 | 2.09 | 2.08 | 2.06 | 2.05 | 0.93 | 0.395 | 0.389 | 0.383 | 0.376 | 0.370 |
| 0.44 | 2.04 | 2.03 | 2.02 | 2.01 | 2.00 | 0.94 | 0.363 | 0.356 | 0.350 | 0.343 | 0.336 |
| 0.45 | 1.98 | 1.97 | 1.96 | 1.95 | 1.94 | 0.95 | 0.329 | 0.321 | 0.314 | 0.307 | 0.299 |
| 0.46 | 1.93 | 1.92 | 1.91 | 1.90 | 1.89 | 0.96 | 0.292 | 0.284 | 0.276 | 0.268 | 0.259 |
| 0.47 | 1.88 | 1.87 | 1.86 | 1.85 | 1.84 | 0.97 | 0.251 | 0.242 | 0.232 | 0.223 | 0.213 |
| 0.48 | 1.83 | 1.82 | 1.81 | 1.80 | 1.79 | 0.98 | 0.203 | 0.192 | 0.181 | 0.169 | 0.156 |
| 0.49 | 1.78 | 1.77 | 1.76 | 1.75 | 1.74 | 0.99 | 0.143 | 0.127 | 0.110 | 0.090 | 0.063 |

NOTE: This table is to be used like a table of logarithms, *e. g.*, the reactance factor corresponding to the power-factor $k=0.816$ is $t=0.708$.

## TABLE II.

### CROSS-SECTION, RESISTANCE AND REACTANCE-FACTORS.

Temperature 20° cent.

Reactance-factors are directly proportional to frequency and to conductivity:

| *For copper wire and* | *For aluminum wire and* |
|---|---|
| 25 cycles divide the reactance-factors given below by 4. | 25 cycles multiply the reactance-factors given below by 0.155. |
| 60 cycles multiply reactance-factors given below by 0.6 | 60 cycles multiply the reactance-factor given below by 0.372. |

| No. B. & S. | Cross-section circular mils. | Ohms per mile at 20° cent. or 68° *fahr.* | | Reactance-factors for 100 per cent. conductivity and 100 cycles per second | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Distance apart of wires in feet. | | | | | | | |
| | | Copper | Aluminum | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | 500,000 | 0.109 | 0.176 | 6.96 | 8.24 | 8.99 | 9.52 | 9.93 | 10.26 | 10.55 | 10.80 |
| | 450,000 | 0.121 | 0.196 | 6.35 | 7.50 | 8.17 | 8.65 | 9.02 | 9.32 | 9.58 | 9.80 |
| | 400,000 | 0.137 | 0.221 | 5.73 | 6.75 | 7.35 | 7.77 | 8.11 | 8.37 | 8.61 | 8.80 |
| | 350,000 | 0.156 | 0.252 | 5.10 | 6.00 | 6.52 | 6.89 | 7.18 | 7.41 | 7.62 | 7.79 |
| | 300,000 | 0.182 | 0.294 | 4.46 | 5.22 | 5.67 | 5.99 | 6.24 | 6.44 | 6.61 | 6.76 |
| | 250,000 | 0.218 | 0.352 | 3.80 | 4.44 | 4.81 | 5.08 | 5.28 | 5.45 | 5.60 | 5.72 |
| 0000 | 212,000 | 0.258 | 0.417 | 3.28 | 3.82 | 4.14 | 4.37 | 4.54 | 4.68 | 4.80 | 4.91 |
| 000 | 168,000 | 0.326 | 0.525 | 2.68 | 3.11 | 3.35 | 3.53 | 3.67 | 3.78 | 3.88 | 3.96 |
| 00 | 133,000 | 0.411 | 0.662 | 2.18 | 2.52 | 2.72 | 2.86 | 2.97 | 3.06 | 3.13 | 3.20 |
| 0 | 106,000 | 0.518 | 0.835 | 1.77 | 2.04 | 2.20 | 2.31 | 2.40 | 2.47 | 2.53 | 2.58 |
| 1 | 83,700 | 0.653 | 1.05 | 1.44 | 1.66 | 1.78 | 1.87 | 1.94 | 2.00 | 2.04 | 2.08 |
| 2 | 66,300 | 0.824 | 1.33 | 1.17 | 1.34 | 1.44 | 1.51 | 1.57 | 1.61 | 1.65 | 1.68 |
| 3 | 52,600 | 1.04 | 1.68 | 0.95 | 1.09 | 1.16 | 1.22 | 1.26 | 1.30 | 1.33 | 1.36 |
| 4 | 41,700 | 1.31 | 2.11 | 0.77 | 0.88 | 0.94 | 0.99 | 1.02 | 1.05 | 1.07 | 1.09 |
| 5 | 33,100 | 1.65 | 2.66 | 0.63 | 0.71 | 0.76 | 0.80 | 0.82 | 0.85 | 0.87 | 0.88 |
| 6 | 26,300 | 2.08 | 3.36 | 0.51 | 0.58 | 0.61 | 0.64 | 0.66 | 0.68 | 0.70 | 0.71 |

NOTE: The above reactance-factors are calculated for solid wire; they are also correct within about one per cent for an ordinary stranded cable or table with hemp core having the same cross-sectional area of conductor.

## TABLE III.

### VALUES OF DROP-FACTOR $M = (1+t_1 t)k^2$

| Reactance-factor | Power-factor Lagging. | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100 | 98 | 95 | 90 | 85 | 80 | 70 |
| 0.0 | 1.00 | 0.96 | 0.90 | 0.81 | 0.72 | 0.64 | 0.49 |
| 0.1 | 1.00 | 0.98 | 0.93 | 0.85 | 0.77 | 9.69 | 0.54 |
| 0.2 | 1.00 | 1.00 | 0.96 | 0.89 | 0.81 | 0.74 | 0.59 |
| 0.3 | 1.00 | 1.02 | 0.99 | 0.93 | 0.86 | 0.78 | 0.64 |
| 0.4 | 1.00 | 1.04 | 1.02 | 0.97 | 0.90 | 0.83 | 0.69 |
| 0.5 | 1.00 | 1.06 | 1.05 | 1.01 | 0.95 | 0.88 | 0.74 |
| 0.6 | 1.00 | 1.08 | 1.08 | 1.05 | 0.99 | 0.93 | 0.79 |
| 0.7 | 1.00 | 1.10 | 1.11 | 1.09 | 1.04 | 0.98 | 0.84 |
| 0.8 | 1.00a | 1.12 | 1.14 | 1.13 | 1.08 | 1.02 | 0.89 |
| 0.9 | 1.00 | 1.14 | 1.17 | 1.17 | 1.13 | 1.07 | 0.94 |
| 1.0 | 1.00 | 1.16 | 1.20 | 1.21 | 1.17 | 1.12 | 0.99 |
| 1.1 | 1.00b | 1.17a | 1.23 | 1.25 | 1.22 | 1.17 | 1.04 |
| 1.2 | 1.00 | 1.19 | 1.26 | 1.29 | 1.26 | 1.22 | 1.09 |
| 1.3 | 1.00 | 1.21 | 1.29 | 1.32 | 1.30 | 1.28 | 1.14 |
| 1.4 | 1.00 | 1.23 | 1.32a | 1.36 | 1.35 | 1.31 | 1.19 |
| 1.5 | 1.00c | 1.25b | 1.35 | 1.40 | 1.39 | 1.36 | 1.24 |
| 1.6 | 1.00 | 1.27 | 1.38 | 1.44a | 1.44 | 1.41 | 1.29 |
| 1.7 | 1.00 | 1.29 | 1.41 | 1.48 | 1.48 | 1.46 | 1.34 |
| 1.8 | 1.00 | 1.31 | 1.44 | 1.52 | 1.53 | 1.50 | 1.39 |
| 1.9 | 1.00 | 1.33 | 1.47b | 1.56 | 1.57 | 1.55 | 1.44 |
| 2.0 | 1.00 | 1.35c | 1.50 | 1.60 | 1.62 | 1.60 | 1.49 |
| 2.1 | 1.00 | 1.37 | 1.53 | 1.64 | 1.66a | 1.65 | 1.54 |
| 2.2 | 1.00 | 1.39 | 1.56 | 1.68 | 1.71 | 1.70 | 1.59 |
| 2.3 | 1.00 | 1.41 | 1.59 | 1.72b | 1.75 | 1.74 | 1.64 |
| 2.4 | 1.00 | 1.43 | 1.62c | 1.76 | 1.80 | 1.79 | 1.69 |
| 2.5 | 1.00 | 1.45 | 1.64 | 1.80 | 1.84 | 1.84a | 1.74 |
| 2.6 | 1.00 | 1.47 | 1.67 | 1.84 | 1.89 | 1.89 | 1.79 |
| 2.7 | 1.00 | 1.49 | 1.70 | 1.88 | 1.93 | 1.94 | 1.84 |
| 2.8 | 1.00 | 1.51 | 1.73 | 1.92 | 1.98 | 1.98 | 1.89 |
| 2.9 | 1.00 | 1.53 | 1.76 | 1.96 | 2.02b | 2.03 | 1.94 |
| 3.0 | 1.00 | 1.55 | 1.79 | 2.00 | 2.07 | 2.08 | 1.99 |
| 3.1 | 1.00 | 1.56 | 1.82 | 2.04c | 2.11 | 2.13 | 2.04 |
| 3.2 | 1.00 | 1.58 | 1.85 | 2.08 | 2.16 | 2.18 | 2.09 |
| 3.3 | 1.00 | 1.60 | 1.88 | 2.12 | 2.20 | 2.22 | 2.14 |
| 3.4 | 1.00 | 1.62 | 1.91 | 2.16 | 2.25 | 2.27b | 2.19 |
| 3.5 | 1.00 | 1.64 | 1.94 | 2.20 | 2.29 | 2.32 | 2.24 |
| 3.6 | 1.00 | 1.66 | 1.97 | 2.24 | 2.34 | 2.37 | 2.29 |
| 3.7 | 1.00 | 1.68 | 2.00 | 2.28 | 2.38 | 2.42 | 2.34 |
| 3.8 | 1.00 | 1.70 | 2.03 | 2.32 | 2.42 | 2.46 | 2.39 |
| 3.9 | 1.00 | 1.72 | 2.06 | 2.35 | 2.47c | 2.51c | 2.44a |

a. Above this point the error in $P$ is less than 5% when $Q \leqq 0.20$.
b. Above this point the error in $P$ is less than 5% when $Q \leqq 0.10$.
c. Above this point the error in $P$ is less than 5% when $Q \leqq 0.05$.

## TABLE IV.

### CAPACITY SUSCEPTANCE PER MILE OF TWO PARALLEL WIRES. FREQUENCY 100 CYCLES PER SECOND.

Capacity susceptance is directly proportional to frequency. For 25 cycles divide the numbers given below by 4; for 60 cycles multiply by 0.6

| Size CM B.&S. | Diam. in Inch | Distance apart of wires in feet. | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 500,000 | 0.707 | $-7.97 \times 10^{-6}$ | $-6.66 \times 10^{-6}$ | $-6.08 \times 10^{-6}$ | $-5.72 \times 10^{-6}$ | $-5.47 \times 10^{-6}$ | $-5.28 \times 10^{-6}$ | $-5.14 \times 10^{-6}$ | $-5.01 \times 10^{-6}$ |
| 450,000 | 0.670 | -7.85 | -6.58 | -6.01 | -5.66 | -5.42 | -5.23 | -5.09 | -4.97 |
| 400,000 | 0.632 | -7.73 | -6.49 | -5.93 | -5.59 | -5.36 | -5.18 | -5.03 | -4.92 |
| 350,000 | 0.591 | -7.59 | -6.39 | -5.85 | -5.52 | -5.29 | -5.11 | -4.97 | -4.86 |
| 300,000 | 0.547 | -7.43 | -6.28 | -5.76 | -5.44 | -5.21 | -5.04 | -4.91 | -4.79 |
| 250,000 | 0.500 | -7.26 | -6.15 | -6.65 | -5.34 | -5.13 | -4.96 | -4.85 | -4.72 |
| 0,000 | 0.460 | -7.10 | -6.04 | -5.56 | -5.26 | -5.05 | -4.89 | -4.76 | -4.65 |
| 000 | 0.410 | -6.90 | -5.90 | -5.43 | -5.15 | -4.95 | -4.79 | -4.67 | -4.57 |
| 00 | 0.365 | -6.71 | -5.76 | -5.31 | -5.04 | -4.85 | -4.70 | -4.58 | -4.48 |
| 0 | 0.325 | -6.53 | -5.62 | -5.20 | -4.94 | -4.75 | -4.61 | -4.49 | -4.40 |
| 1 | 0.280 | -6.36 | -5.49 | -5.09 | -4.84 | -4.66 | -4.52 | -4.41 | -4.32 |
| 2 | 0.258 | -6.20 | -5.37 | -4.99 | -4.74 | -4.57 | -4.44 | -4.33 | -4.25 |
| 3 | 0.229 | -6.04 | -5.25 | -4.89 | -4.65 | -4.49 | -4.36 | -4.26 | -4.07 |
| 4 | 0.204 | -5.89 | -5.15 | -4.79 | -4.56 | -4.41 | -4.28 | -4.19 | -4.10 |
| 5 | 0.182 | -5.75 | -5.04 | -4.70 | -4.48 | -4.33 | -4.21 | -4.41 | -4.03 |
| 6 | 0.162 | -5.62 | -4.94 | -4.61 | -4.40 | -4.15 | -4.14 | -4.05 | -3.97 |

NOTE: The capacity susceptances given in this table are for solid wires; a stranded wire has a capacity susceptance about 3 per cent. greater. For special cables having hemp cores use the susceptance corresponding to the actual diameter of the table; the susceptance is a function of the diameter, not of the cross section.

The charging current per mile of *single phase* line (2 miles of wire) is equal to the above factors multiplied by the volts between wires; for a *three phase line* the charging current per wire per mile of line (3 miles of wire) is equal to the product of the above factors and the volts between wires multiplied by 1.155.

## APPENDIX

The following table, giving the per cent. power loss per mile per 1000 kw. delivered at unity power-factor over a three-phase copper line, will be found useful in determining the size of wire required to transmit a given amount of power under given conditions.

PER CENT. POWER LOSS PER MILE PER THOUSAND KILOWATTS DELIVERED THREE-PHASE SYSTEM, COPPER WIRE, UNITY POWER-FACTOR.

| Size B. & S. | Cir. mils | Pounds per mile 3-stranded wires | | Kilovolts delivered | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Copper | Aluminum | 2 | 6 | 10 | 20 | 30 | 40 | 50 | 60 | 80 | 100 |
| | 500,000 | 24,200 | 7,290 | 2.7 | 0.31 | 0.11 | 0.027 | 0.012 | 0.0069 | 0.0044 | 0.0031 | 0.0017 | 0.0011 |
| | 450,000 | 21,700 | 6,500 | 3.1 | 0.34 | 0.12 | 0.031 | 0.014 | 0.0076 | 0.0049 | 0.0034 | 0.0019 | 0.0012 |
| | 400,000 | 19,300 | 5,830 | 3.4 | 0.38 | 0.14 | 0.034 | 0.015 | 0.0086 | 0.0055 | 0.0038 | 0.0021 | 0.0014 |
| | 350,000 | 16,900 | 5,100 | 3.9 | 0.44 | 0.16 | 0.039 | 0.017 | 0.0098 | 0.0063 | 0.0044 | 0.0025 | 0.0016 |
| | 300,000 | 14,500 | 4,370 | 4.6 | 0.51 | 0.18 | 0.046 | 0.020 | 0.011 | 0.0073 | 0.0051 | 0.0029 | 0.0018 |
| | 250,000 | 12,100 | 3,650 | 5.5 | 0.61 | 0.22 | 0.055 | 0.024 | 0.014 | 0.0088 | 0.0061 | 0.0034 | 0.0022 |
| 0000 | 211,600 | 10,200 | 3,080 | 6.5 | 0.72 | 0.26 | 0.065 | 0.029 | 0.016 | 0.010 | 0.0072 | 0.0041 | 0.0026 |
| 000 | 167,800 | 8,130 | 2,450 | 8.2 | 0.91 | 0.33 | 0.082 | 0.036 | 0.020 | 0.013 | 0.0091 | 0.0051 | 0.0033 |
| 00 | 133,100 | 6,430 | 1,940 | 10 | 1.1 | 0.41 | 0.10 | 0.046 | 0.026 | 0.016 | 0.011 | 0.0064 | 0.0041 |
| 0 | 105,500 | 5,100 | 1,540 | 13 | 1.4 | 0.52 | 0.13 | 0.058 | 0.033 | 0.021 | 0.014 | 0.0081 | 0.0052 |
| 1 | 83,690 | 4,040 | 1,220 | 16 | 1.8 | 0.65 | 0.16 | 0.072 | 0.041 | 0.026 | 0.018 | 0.010 | 0.0065 |
| 2 | 66,370 | 3,220 | 969 | 21 | 2.3 | 0.83 | 0.21 | 0.092 | 0.052 | 0.033 | 0.023 | 0.013 | 0.0083 |
| 3 | 52,630 | 2,540 | 768 | 26 | 2.9 | 1.0 | 0.26 | 0.12 | 0.065 | 0.042 | 0.029 | 0.016 | 0.010 |
| 4 | 41,740 | 2,010 | 609 | 33 | 3.7 | 1.3 | 0.33 | 0.15 | 0.082 | 0.053 | 0.037 | 0.021 | 0.013 |
| 5 | 33,100 | 2,002 | | 41 | 4.6 | 1.7 | 0.41 | 0.18 | 0.10 | 0.066 | 0.046 | 0.026 | 0.017 |
| 6 | 26,250 | 1,587 | | 52 | 5.8 | 2.1 | 0.52 | 0.23 | 0.13 | 0.084 | 0.058 | 0.033 | 0.021 |

NOTE: The above table is calculated for copper wire and unity power-factor. The size wire to use under other conditions can be readily found by determining from the table the size of copper wire to use in case the power factor were unity and then for the actual conditions select a wire as follows:

*For copper wire and*

90 *per cent. power-factor*, take a wire of 25 per cent. greater cross section (on B. & S. gauge a wire larger by one number).

80 *per cent power-factor*, take a wire of 60 per cent. greater cross section (on B. & S. gauge a wire larger by two numbers.

*For Aluminum Wire and*

100 *per cent. power-factor* take a wire of 60 per cent. greater cross section (on B. & S. gauge a wire larger by two numbers).

90 *per cent. power-factor*, take a wire of twice the cross section (on B. & S. gauge a wire larger by three numbers).

80 *per cent. power-factor*, take a wire of two and one-half times the cross section (on B. & S. gauge a wire larger by four numbers).

*For any voltage not given in the table*,

the size wire to use can be readily determined by remembering that the cross-section for a given per cent. power loss varies inversely as the square of the voltage; *e.g.*, for 11 kilovolts delivered multiply the cross-section corresponding to 10 kilovolts by $\left(\frac{10}{11}\right)^2 = 0.83$.

*Example.* 20,000 kilowatts is to be transmitted 30 miles over a three-phase system with a total loss in the line of 10% of the power delivered, the delivered pressure to be 60,000 volts; to find the size wire required.

The power loss per mile per 1000 kw. delivered is

$$\frac{10}{30 \times 20} = 0.017 \text{ per cent.}$$

From the table the nearest size copper wire corresponding to 60 kilovolts and a loss of 0.017 per cent. is No. 1 B. & S. (this will give a total loss slightly greater than 10 per cent.) If the power-factor of the load at the end of the line is 90%, No. 0 copper should be used (see note below table); if the power-factor is 80%, No. 00 wire should be used.

If aluminum is to be used, the size wire under the various conditions would be; for unity power-factor, No. 00; for 90% power-factor, No. 000, and for 80% power-factor, No. 0000.

When the size and kind of wire has been determined, the exact power loss and pressure drop can be calculated by the formulas given on the preceding pages.

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## DISCUSSION ON "A TRIGONOMETRIC METHOD FOR THE SOLUTION OF ALTERNATING-CURRENT PROBLEMS," ATLANTIC CITY, N. J., JULY 2, 1908

**Comfort A. Adams:** Eight or ten years ago I worked out, for the purpose of transmission line calculations, a method which, with tables and curves, was an almost exact equivalent of Mr. Pender's method. If one had frequent occasion to make transmission line calculations these tables and curves would be a great assistance, but for infrequent use it takes longer to become familiar with the method than to solve the problem by the long way.

Moreover, I cannot help viewing a matter of this sort from the standpoint of the teacher, and from that standpoint it seems to me that these short-cut methods are undesirable since they do not bring out step by step the physical meaning of the problem; they do not keep one reminded of exactly what one is doing, and an error is less likely to be detected. The natural method has proved more serviceable in my own work, where a given type of problem is considered occasionally, and I think it far more valuable for students. However, I do not wish to minimize the value of any such labor-saving device, as it has a legitimate field where it serves a most useful purpose.

**W. A. Del Mar** (by letter): The treatment of alternating-current problems has been subject to rapid evolution. When Dr. Steinmetz's method of imaginary quantities appeared it seemed that the summit of development in that line had been reached, but Mr. Pender's method is as much in advance of the Steinmetz method as the latter was of the plain vector method which preceded it. It is a more important advance than that due to Steinmetz's method, because it places the solution of alternating-current problems within the reach of those of very limited mathematical training.

To the teachers Mr. Pender's method should particularly commend itself, as it can be quickly acquired and students can be taught the solution of alternating-current problems before they reach the fairly advanced mathematics. One effect of this would be the possibility of inculcating elementary ideas about alternating currents before the professor of mathematics had propounded the theory of vectors and imaginary quantities.

A preliminary reading of the new method gave the impression that for didactic purposes it would suffer from the disadvantage of not offering a direct physical understanding of the various operations. This impression soon vanished, however, when the ease of working became apparent, for the observations of the writer have led him to believe that only a small portion of technical graduates understand the theory of alternating-current machinery so that they can apply it to the solution of practical problems. This condition arises either from indifference to mathematics, or from the ease with which the subject is forgotten in after years. The simplicity of Dr. Pender's method overcomes these two difficulties in an admirable way.

The writer has had occasion to try the new method to solve a number of problems, including the eddy-current brake and transmission problems, and has found the application extremely simple in every case.

**L. W. Rosenthal** (by letter): I should like to point out the character of the error resulting from the approximation for $E_0$ between formulas (17) and (18). Denoting the power-factor angle of the load by $\phi$ and that of the line by $\theta$, the error will depend on $(\theta+\phi)$ for leading currents and on $(\theta-\phi)$ for lagging currents. The error also depends on the per cent. voltage loss. The attached curves show the correction which must be applied to the approximate values of $D$, from which it is evident that for the range of 0 to 20 per cent. loss the approximation is sufficiently close only to about 45°. The values of $(\theta-\phi)$ for

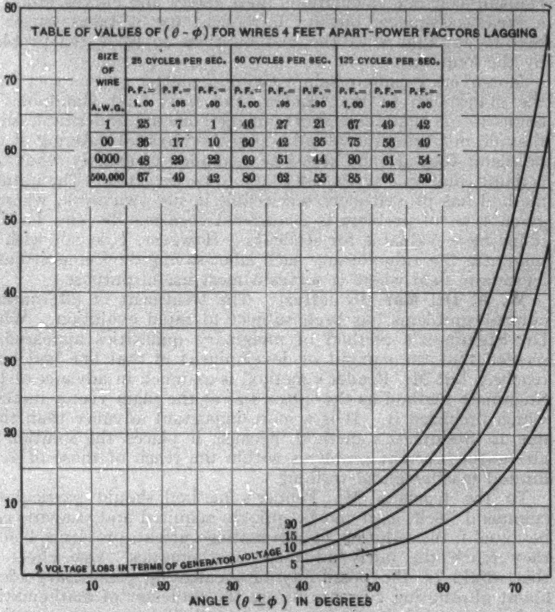

TABLE OF VALUES OF $(\theta-\phi)$ FOR WIRES 4 FEET APART–POWER FACTORS LAGGING

| SIZE OF WIRE | 25 CYCLES PER SEC. | | | 60 CYCLES PER SEC. | | | 125 CYCLES PER SEC. | | |
|---|---|---|---|---|---|---|---|---|---|
| A.W.G. | P.F.= 1.00 | P.F.= .95 | P.F.= .90 | P.F.= 1.00 | P.F.= .95 | P.F.= .90 | P.F.= 1.00 | P.F.= .95 | P.F.= .90 |
| 1 | 25 | 7 | 1 | 46 | 27 | 21 | 67 | 49 | 42 |
| 00 | 36 | 17 | 10 | 60 | 42 | 35 | 75 | 56 | 49 |
| 0000 | 48 | 29 | 22 | 69 | 51 | 44 | 80 | 61 | 54 |
| 500,000 | 67 | 49 | 42 | 80 | 62 | 55 | 85 | 66 | 59 |

FIG. 1

various wires, frequencies, and lagging power-factors are shown in the table on Fig. 1.

As an extreme case of the possible error, suppose in the first numerical example that the frequency be taken at 125 cycles per second, the power-factor at 100 per cent., and the load reduced to 3500 kw. in order to obtain about the same voltage loss. The exact formula (17) will then give a voltage loss of 21.8 per cent., while the approximate formula (18) shows a loss of 12.8 per cent. In other words, the "approximate value" requires a correction of 70 per cent., as is also shown by the curves at 75° and a loss of 18 per cent. of the generated volts, corresponding to 21.8 of the received volts. In the example chosen by the author $(\theta - \phi)$ equals 17°, and hence the error is small.

Although the author has drawn attention to the increasing error of the approximation by the letters *a*, *b*, and *c* in Table III, yet it would have been better to omit the values below *c*, which approximately correspond to $(\theta \pm \phi)$ equals 40°. It seems, therefore, that for high frequencies or power-factors, and for large wires or per cent. voltage losses, the approximate formulas (18) may give erroneous results. They should not be used in any case where the drop-factor $M$ is below the $c$ of its column.

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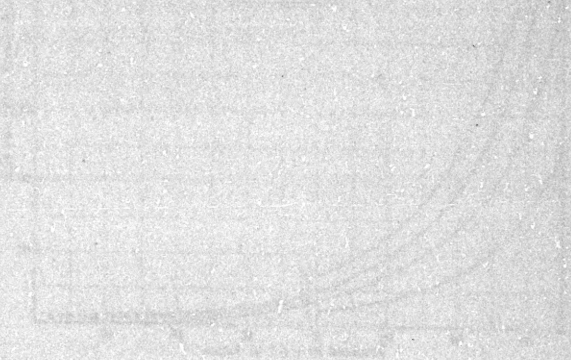

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# THE RELATIVE PROPORTIONS OF COPPER AND IRON IN ALTERNATORS

BY CARL J. FECHHEIMER

Many radical changes have accompanied the rapid development of alternating-current generators. In the early days, when alternators were designed by rule-of-thumb methods, the relative proportion of copper to iron was high. These machines had very poor inherent regulation, and in many cases failed to give the voltage for which they were designed. These "copper machines" were relatively light, and were considerably cheaper than the "iron machines" which succeeded them. The iron machines, though much heavier and more expensive than their predecessors, had much better regulation. Following this, the characteristics of alternators were more carefully studied so that the designer was able to reduce the weight and again approach the copper machine. Competition between the various manufacturing companies made it necessary for their engineers to design cheaper machines, resulting in a compromise between the "copper" and "iron" machines. We are now at this period, and the designer is to-day confronted with the question: what shall be the relative proportions of copper and iron in this machine? Doubtless the answer is, so to proportion the iron and copper as to obtain the cheapest possible machine.

The usual method of carrying this out consists in designing a number of machines with different fluxes, and possibly different diameters, and, after calculating the weights and costs of the various parts, to select that design which is believed to be the most desirable. This method requires a great amount of time, and is very laborious. In this paper the writer has endeavored to bring out a method which will enable the designer to determine, after a few substitutions, what value of flux to employ to give the cheapest machine. He has made no attempt to determine mathematically the best diameter to use; in fact, he has assumed certain simple relations involving the diameter, such as the ratio of pole axial length to pole pitch. However, the relations are such that the designer, having studied and designed a number of machines in the past, can readily decide upon the best values to use for these constants.

So many variables enter into the design of alternators that it has been essential to establish definite relations between some of them in order to reduce their number. Some of these relations are empirical, in which case the evaluation of the constants involved in the empirical equations is left to the designer. Other relations, such as the fundamental equation used for determining the temperature rise of the armature coils, and the relation between field and armature ampere-turns per pole, are combinations of fundamental principles with empirical constants.

Briefly, the method which the writer has pursued in this paper is as follows: Equations are derived for the weights of the principal parts of the alternator, the weight in each case being expressed as some factor which is easily determined, multiplied by some power of the flux per pole. The weight of these parts is then multiplied by the price per pound of material used and by some other factor to allow for the unavoidable scrap material, and also for some of the parts not included in the equations, as for example, the stator teeth and the spider arms. The sum of these costs will give the cost of the material in the principal parts of the machine in terms of the flux. We can find what value of flux to employ to give the minimum cost of material in the parts considered by differentiating the equation obtained with respect to the flux, equating to zero, and solving the equation for the flux. Having determined the flux, the number of conductors necessary to give the desired electromotive force at once follows. The arrangement of these conductors, the diameter and length of the machine, the dimensions of the field conductor, etc., are left to the judgment of the designer, as has been the custom in the past.

The method is intended to apply to revolving-field alternators having rectangular poles. It is quite possible, however, to apply the method to machines of the revolving-armature type, although, judging from present indications, this type of machine will be built very little in the future. The round-pole machine necessitates so large a diameter that the cost of this type of machine would generally be much greater than the rectangular pole machine, even though there would be a considerable saving in field copper. There are special cases in which the round-pole machine is desirable, and in such cases it would be possible to modify the equations as derived by the writer.

The cost of the bases, shafts, bearings, and other "dead" material increases somewhat with the flux, but it is impossible to consider every detail in determining the most suitable value of flux to use. The labor also increases somewhat with the flux. As this, omitting the burden, is usually much smaller than the material, it has been neglected in the method which has been employed. The freight also increases with the quantity of flux employed, as a large flux machine means a machine that will be great in weight. All things considered, it will usually be best, from the standpoint of cost, to select a value for the flux which will be slightly less than that given by means of the equations.

If we were to employ a value of flux as given by the equation for the cheapest machine, it would be impossible in some cases, with our present methods of cooling, to prevent an excessive temperature rise, as, for example, in some of the small, high-speed, 25-cycle machines. In these, the fields become so crowded near the bases of the poles that it is very difficult to put sufficient copper in the fields to keep their temperature rise within limits, especially when the machine is to operate at low power-factor. In such cases, the best we can do is to approach as near to the copper machine as possible. In a few other cases there are limits which prevent the direct application of the writer's method.

In some cases it is possible to reduce the weight below the weight of the cheapest machine as determined by the writer's method, without sacrificing the electrical qualities of the machine. In such cases it may be advisable to build the lightest machine rather than the machine which will be the cheapest for the factory to build, especially when the machine is to go to some district to which the freight rates are very great.

There are many cases in which it is desirable to employ some other means of procedure than that brought out by the writer in this paper. The writer believes his method to be especially applicable to alternators which are to be entirely new or nearly so. For machines in which a large number of old parts can be used, it is usually best to make use of them rather than to build an entirely new machine in which the material is used most economically.

The method is only an approximation, but is believed by the writer to be sufficiently accurate for commercial purposes; for when we consider the variation in weight of yoke castings made from the same pattern, the not inconsiderable difference in temperature rise of duplicate machines, and the wide limits between which the market value of the raw material fluctuates (copper in particular), a rough approximation is doubtless sufficiently accurate.

As previously stated, no attempt has been made to determine mathematically the best diameter and axial length to employ. Within reasonable limits, a decrease in diameter (and increase in length) usually necessitates an increase in copper and a reduction in iron and total weight. Conversely, an increase in diameter requires an increase in total iron and a reduction in copper. This follows from the well known facts that the ventilation in a long machine is poorer than in a short machine; that the field mean-turn is greater in the former than in the latter; that the weight of the yoke and spider increase more rapidly with an increase in diameter than with an equivalent increase in length, etc. The labor is usually slightly less on the machine having the small diameter. The freight is generally less on the small diameter machine. There are some cases, as in engine-type, 60-cycle generators of small output, in which the machines must be made large in diameter to prevent so small a pole pitch as to cause the field to become too crowded. On the other hand, the diameter is often limited by the peripheral speed. The choice of diameter and length of machine depend upon the judgment of the designer.

The writer appreciates the fact that a mathematical treatment of this kind has a tendency to cause the designer to drift away from the physical conception of the problem in hand. The designer can, however, check up his calculations roughly as he proceeds, by comparing the weight of each part with the weight of corresponding parts of machines previously built, he having assumed an approximate value for the flux. He can further simplify his calculations by plotting curves. For example, he can plot a series of curves to aid him in evaluating $K^x$ in equation (42). He may plot $K^{x}$ against the number of poles, $p$, fixing the value of $K^{II}\,K^{IV}$, and plotting different curves for different values of $B_a$, the armature core density.

## NOTATION

$a$ = number of active conductors per slot = number of conductors per slot divided by number of parallel circuits in armature.

$A$ = ampere conductors per inch of armature periphery, full load.

$B_a$ = flux density in armature core in kilolines per sq. in.

$B_{f.r.}$ = flux density in field ring in kilolines per sq. in.

$B_p$ = flux density in poles in kilolines per sq. in.

$d_1$ = outside diameter of field ring in inches.

$d_2$ = inside diameter of field ring in inches.

$D_1$ = outside diameter of armature laminations, in inches.

$D_2$ = inside diameter of armature laminations, in inches.

$E$ = alternating-current electromotive force per phase or per leg if star connected.

$E'$ = direct-current exciting electromotive force per pole.

$F_a$ = equivalent section in square inches of one active armature conductor = section of one conductor multiplied by the number of parallel paths in armature.

$F_f$ = section in square inches of field conductor.

$H$ = radial dimension of pole including head.

$I_a$ = alternating current amperes per leg in armature.

$I_f$ = direct current amperes excitation on full field.

$k$ = distribution factor = ratio of vector to algebraic sum of electromotive forces induced in armature conductors in one leg.

$K$ = ratio of net to gross iron in poles.

$K'$ = ratio of field ampere-turns per pole required for full field to the armature ampere conductors per pole with full load.

$K^{II}$ = ratio of $W$ to $\lambda$ (ratio of tangential dimension of pole to axial length of pole).

$K^{III}$ = resistivity in micro-ohms of an inch cube of copper at the temperature of the fields when hot = .85 approx.

$K^{IV}$ = ratio of pole length $\lambda$ to pole pitch $\tau$

$$K^{V} = \frac{3130\,K^{III}\,\sigma}{K\,B_p\,P_f}\;\frac{(K^{II}+1)^2}{K^{II}}\left[\frac{P_a\,K'}{k\sim}\right]^2$$

$K^{\text{VI}}$ = factor by which the product of amperes per square inch and ampere conductors per inch should be divided to give the temperature rise in degrees centigrade of armature coils.

$K^{\text{VII}}$ = ratio of length of armature end connections per coil to pole pitch.

$$K^{\text{VIII}} = \frac{323 \times 10^6 \; (2\,K^{\text{IV}} + K^{\text{VII}})}{p\,T\,K^{\text{VI}}} \left[\frac{P_a}{\sim k}\right]^2$$

$K^{\text{IX}}$ = ratio of net iron in armature to axial length of pole $\lambda$.

$$K^{\text{X}} = \frac{22{,}000}{B_a} \sqrt{\frac{K\,K^{\text{II}}\,B_p}{10\,\sigma}} \left(\frac{1}{B_a\,K^{\text{IX}}} + \frac{0.636\,p\,\sigma}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_p}\right)$$

$K^{\text{XI}}$ = coefficient used for determining weight of yoke =

$$\frac{W_y}{D_1^{\frac{4}{3}}\,\lambda^{\frac{1}{3}}}$$

$$K^{\text{XII}} = 565\,K^{\text{XI}} \sqrt{\frac{p}{K^{\text{IV}}}} \left[\frac{.318\,\sigma\,p}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_p} + \frac{1.5}{K^{\text{IX}}\,B_a}\right]$$

$K^{\text{XIII}}$ = ratio of pole radial heighth $H$, to square root of pole waist $W$.

$$K^{\text{XIV}} = 1580\,p\,K^{\text{XIII}}\,(K^{\text{II}}/K)^{\frac{1}{4}}\,(\sigma/B_p)^{\frac{5}{4}}$$

$$K^{\text{XV}} = \frac{4450\,\sigma'}{B_{f.r.}} \sqrt{\frac{K\;K^{\text{II}}\,B_p}{\sigma}} \left(\frac{p\,\sigma}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_p} - \frac{1.57\;\sigma'}{B_{f.r.}}\right)$$

$$K^{\text{XVI}} = \frac{4900\,\sigma'}{B_{f.r.}}\,K^{\text{XIII}} \left(\frac{\sigma\,K^{\text{II}}}{K\,B_p}\right)^{\frac{1}{4}}$$

$(M.T.)_a$ = mean length of turn, in inches, of armature coil.
$(M.T.)_f$ = mean length of turn, in inches, of field coil.
$N$ = number of field turns per pole.
$n$ = number of phases.
$p$ = number of poles.
$p_a$ = price, in dollars per pound, of armature copper, including transportation, etc.
$p_{ai}$ = price, in dollars per pound, of armature active iron, including transportation, etc.
$p_f$ = price, in dollars per pound, of field copper, including transportation, etc.

$p_{f.r.}$ = price, in dollars per pound, of field ring material, including transportation, etc.

$p_p$ = price, in dollars per pound, of pole iron, including transportation, etc.

$p_y$ = price, in dollars per pound, of yoke iron, including transportation, etc.

$P_a$ = rated kilovolt-ampere output of alternator.

$P_f$ = kilowatts excitation required for full field on alternator.

$S$ = number of stator slots per phase per pole.

$S_a$ = cost of armature copper in dollars.

$S_{ai}$ = cost of armature active iron in dollars.

$S_f$ = cost of field copper in dollars.

$S_m$ = cost of material for principal parts of alternator in dollars.

$S_{f.r.}$ = cost of field ring in dollars.

$S_p$ = cost of poles in dollars.

$S_y$ = cost of yoke in dollars.

$T$ = temperature rise in degrees centigrade, of armature coils.

$W$ = pole waist, or tangential dimension of pole.

$W_a$ = weight in pounds of armature copper.

$W_{ai}$ = weight in pounds of armature active iron.

$W_f$ = weight in pounds of field copper.

$W_{f.r.}$ = weight in pounds of field ring.

$W_p$ = weight in pounds of poles.

$W_y$ = weight in pounds of yoke.

$X$ = full field ampere-turns per pole.

### GREEK LETTERS

$\alpha_1 = p_f K^{\mathrm{v}}$

$\alpha_2 = p_a K^{\mathrm{viii}}$

$\alpha_3 = p_{ai} K^{\mathrm{x}} + p_{f.r.} K^{\mathrm{xv}}$

$\alpha_4 = p_y K^{\mathrm{xii}}$

$\alpha_5 = p_p K^{\mathrm{xiv}} - p_{f.r.} K^{\mathrm{xvi}}$

$\Delta$ = current density in armature copper, amperes per square inch

$\lambda$ = length of pole parallel to shaft.

$\sigma$ = pole leakage factor = $\dfrac{\text{flux in one pole}}{\text{useful flux per pole.}}$

$\sigma'$ = field ring leakage factor.

$\tau$ = pole pitch in inches.

$\phi$ = flux in megalines per pole.

$\sim$ = frequency, cycles per second.

## WEIGHT AND COST OF MATERIAL REQUIRED FOR ALTERNATORS.

### FIELD COPPER

We have the following well-known fundamental equations:

$$\phi = \frac{100\,E}{2.22\,a\,S \sim p\,k} \tag{1}$$

$$A = \frac{a\,S\,I_a\,n}{\tau} \tag{2}$$

$$B_p = \frac{10^3\,\phi\,\sigma}{W \cdot \lambda\,K} \tag{3}$$

Combining the above equations, we have:

$$\phi = \frac{100\,E\,I_a\,n}{2.22\,p\,k \sim A\,\tau} = \frac{W\,\lambda\,B_p \cdot K}{10^3\,\sigma} \tag{4}$$

The ratio of the field ampere-turns per pole required for full field to the armature ampere conductors per pole is fixed, within reasonable limits, by the regulation required of the alternator, the power-factor of the circuit, the amount of overload required of the generator, and the manner in which the magnetic circuit is proportioned; it being understood that the alternator is to give its normal voltage when operating at the proper frequency and subjected to the specified overload at the power-factor of the circuit. This ratio varies from 1 to 2.2 in polyphase machines, depending upon the factors given above, and in accordance with guarantees required by consulting engineers at the present time. Calling this ratio $K'$, we have:

$$X = K'\,A\,\tau \tag{5}$$

Combining (4) and (5),

$$X = \frac{10^5\,E\,I_a\,n\,K'\,\sigma}{2.22\,p\,k \sim W\,\lambda\,B_p\,K}$$

But $E\,I_a\,n = 10^3\,P_a$ (6)

Therefore,

$$X = \frac{10^8\,P_a\,K'\,\sigma}{2.22\,p\,k \sim W\,\lambda\,B_p\,K} \tag{7}$$

The following equations are well known:

$$F_f = \frac{K^{\mathrm{III}}\,X\,\,(M.T.)_f}{10^6\,E'} \tag{8}$$

$$W_f = 0.318\,(M.T.)_f\,N.\,p\,F_f \tag{9}$$

And the following is sufficiently accurate for the present estimate, when the poles are rectangular in section:

$$(M.T.)_f = 2.2\ (W + \lambda) \tag{10}$$

Combining (8), (9) and (10),

$$W_f = \frac{1.54\ K^{\text{III}}\ X\ p\ N\ (W + \lambda)^2}{10^6\ E'} \tag{11}$$

The designer will know approximately at the start what the ratio of the tangential dimension, $W$, of the pole, to the axial length of the pole, will be. This ratio varies from 1 in high speed 25 cycle machines to 4.0 in slow speed 60 cycle generators. Calling this ratio $K^{\text{II}}$, we have

$$W = K^{\text{II}}\ \lambda \tag{12}$$

The amperes excitation on full field is:

$$I_f = \frac{X}{N} \tag{13}$$

Combining (11), (12) and (13),

$$W_f\ I_f = \frac{1.54\ (K^{\text{II}} + 1)^2\ \lambda^2\ p\ K^{\text{III}}\ X^2}{10^6\ E'} \tag{14}$$

Combining (7) and (14),

$$W_f\ (I_f\ E'\ p) = 31.3\ K^{\text{III}}\ (K^{\text{II}} + 1)^2\ \lambda^2\ 10^8 \left(\frac{P_a\ K'\ \sigma}{k \sim W\ \lambda\ B_p\ K}\right)^2 \tag{15}$$

But $$I_f\ E'\ p = 10^3\ P_f \tag{16}$$

and from (3),

$$W\ \lambda\ B_p\ K = 10^8\ \sigma\ \phi \tag{17}$$

The designer will recognize the fact that the ratio of pole length to pole pitch is very nearly fixed, varying from .5 in high speed 25 cycle machines to 2 in slow speed 60 cycle machines. Calling this ratio $K^{\text{IV}}$, we have

$$\lambda = K^{\text{IV}}\ \tau \tag{18}$$

Combining (12) and (18),

$$W = K^{II} K^{IV} v \tag{19}$$

Combining (3), (18) and (19),

$$\lambda = 10 \sqrt{\frac{10 \phi \sigma}{K^{II} K B_p}} \tag{20}$$

Combining (15), (16), (17) and (20),

$$W_f P_f = \left\{ \frac{3130 K^{III} \sigma}{K B_p} \frac{(K^{II}+1)^2}{K^{II}} \left[ \frac{P_n K}{\sim k} \right]^2 \right\} \frac{1}{\phi} \tag{21}$$

Equation (21) illustrates a condition with which designers are familiar; that is, without sacrificing the good qualities of the generator, the excitation can be reduced only at the expense of field copper; and if we approach a copper machine by decreasing the flux, it results in a proportional increase in weight of field copper for a given excitation.

It is usually known at the start what full field excitation to allow, this being limited in some cases by heating; while in other cases it is necessary to reduce the excitation to prevent its becoming too large a percentage of the output of the alternator. As typical examples of the first class, we have the moderate and high speed 25 cycle alternators up to about 500 kw. output, in which the output of the machine must be reduced to prevent excessive field heating when operating at low power factors. As examples of the second class we have fairly large (1000 kw. or over) engine-type, 60-cycle generators, the field heating of which seldom exceeds 40 degrees rise when operating on full field, the single layer edge-wound field being used in both cases.* Therefore, the designer, knowing the full field excitation in kilowatts at the start (having made a study of the limiting conditions), will know the value of all of the quantities in equation (21), except the flux $\phi$ and the weight of field copper $W_f$. Hence,

$$W_f = \left\{ \frac{3130 K^{III} \sigma}{K B_p P_f} \frac{(K^{II}+1)^2}{K^{II}} \left[ \frac{P_a K}{\sim k} \right]^2 \right\} \frac{1}{\phi} \tag{22}$$

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* A means of determining that value to assign to the excitation, which will make the cost of the entire equipment a minimum, is given in the appendix.

And $$W_f = K^{v}\,\frac{1}{\phi} \qquad (23)$$

Where $K^{v}$ is the expression in the brace in equation (22).

If $p_f$ represent the price in dollars of one pound of field copper, the total cost of field copper for the alternator is:

$$S_f = p_f\,K^{v}\,\frac{1}{\phi} \qquad (24)$$

## ARMATURE COPPER.

The weight of copper required for the armature of an alternator depends primarily upon the temperature rise per watt loss per square inch of radiating surface. The loss is not only affected by the core loss and copper loss due to the resistance of the copper, but also by the eddy-current loss in the copper. The core loss differs considerably in duplicate machines, due chiefly to variation in material. All revolving-field alternators depend for the cooling of their armatures upon the air thrown into the stator by the rotating element. It frequently happens that this air is not uniformly distributed over the surface of the armature, causing a greater cooling at one side than at the other side of the armature, resulting in a greater elevation in temperature in one part of the armature than in another. The designer must allow for the maximum elevation in temperature. With the inconsistent data obtained from heat runs on a large number of machines, it is next to impossible to obtain any reliable means of predetermining the temperature rise within a few per cent. The best that can be done is to obtain a rough approximation. Machines having the same quantity of air thrown upon each square inch of stator surface per unit of time, and when worked at the same magnetic densities in the stator, will, when operated on open circuit, have approximately the same elevation on the stator iron. It is therefore reasonable that the incremental heating due to the copper loss be alone considered.

It may be easily shown that the watts copper loss (due to resistance only) per square inch of surface is proportional to the product of ampere-conductors per inch and the current density in the armature conductor (in amperes per square inch). The surface is taken as the cylindrical surface of the armature iron plus the surface of the end-connections. Hence, we may write:

$$T = \frac{A\,\Lambda}{K^{vi}} \qquad (25)$$

$T$ is the temperature rise in degrees centigrade, $A$ the ampere conductors per inch, and $\Delta$ the density in amperes per square inch. $K^{VI}$ varies in values from $1.8 \times 10^4$ in poorly ventilated, or slow speed, high voltage machines to $9 \times 10^4$ in low-voltage, well ventilated machines, not having appreciable eddy current loss in the conductors. These values of $K^{VI}$ are consistent with modern practice in methods employed in cooling the stators of revolving field alternators. If at some future time the methods of cooling are improved, $K^{VI}$ should be modified accordingly.

Since

$$\Delta = \frac{I_a}{F_a}, \tag{26}$$

where $I_a$ = alternating current amperes per leg, and $F_a$ = section of one active armature conductor, we have, by combining with (2) and (25),

$$a\,S = \frac{T\,F_a\,K^{VI}\,\tau}{I_a^2\,n} \tag{27}$$

The weight of armature copper in pounds is:

$$W_a = .318\,(M.T.)_a\,F_a\,a\,\frac{S}{2}\,n\,p \tag{28}$$

The mean length of turn is given by:

$$(M.T.)_a = 2\,\lambda + K^{VII}\,\tau \tag{29}$$

$K^{VII}$ has a value of about 4.2 for 2 or 3 phase chain windings and about 3.6 for full pitch double layer windings. It is somewhat greater than 4.2 for chain windings intended for high voltage machines; and for short pitch double layer windings, it should be correspondingly reduced.

Combining (27), (28), (29) and (18),

$$W_a = \left[\frac{.159\,(2\,K^{IV} + K^{VII})\,T\,K^{VI}\,p}{I_a^2}\right](\tau\,F_a)^2 \tag{30}$$

Eliminating $a\,S$ between (1) and (27),

$$F_a\,\tau = \frac{100\,E\,I_a^2\,n}{2.22\,p \sim k\;T\,K^{VI}}\;\frac{1}{\phi} \tag{31}$$

Combining (30), (31) and (6),

$$W_a = \left\{ \frac{323 \times 10^6 \ (2\,K^{\text{IV}} + K^{\text{VII}})}{p\,T\,K^{\text{VI}}} \left[ \frac{P_a}{\sim k} \right]^2 \right\} \frac{1}{\phi^2} \tag{32}$$

And

$$W_a = K^{\text{VIII}} \frac{1}{\phi^2} \tag{33}$$

where $K^{\text{VIII}}$ is the expression in the brace in equation (32).

This equation illustrates how rapidly the cost of copper increases as the flux is reduced and we approach a "copper" machine.

If $p_a$ represent, in dollars per pound, the price of copper used in the armature, then the cost of armature copper is:

$$S_a = p_a\,K^{\text{VIII}} \frac{1}{\phi^2} \tag{34}$$

The value of $K^{\text{VIII}}$ should be increased by about 5 to 15 per cent. to allow for scrap.

### ARMATURE ACTIVE IRON.

In punching the laminations for the armature there is always an unavoidable amount of scrap, varying from 25 to 60 per cent. This scrap, or at least a portion of it, should be charged up to the cost of the material required. It complicates the equations considerably, to bring in the iron in the teeth, while it is not very difficult to form an equation considering only the iron behind the teeth. As it is necessary to add a percentage for the scrap material, it is easy to increase this percentage so as to include the iron in the teeth. This is the method pursued, no attempt being made in the equations to find to what extent the weight of the teeth is affected by the flux.

Neglecting the fact that the diameter of the armature is not exactly the same at the bore as at the tooth roots, we have

$$W_{ai} = 0.28\,(D_1^2 - D_2^2)\,\frac{\pi}{4}\,K^{\text{IX}}\,\lambda = 0.22\,(D_1 - D_2)\,(D_1 + D_2)\,K^{\text{IX}}\,\lambda \tag{35}$$

Since we are considering only that portion of the armature active iron through which the flux passes after emerging from the teeth, the depth of the armature punching is $\frac{1}{2}(D_1 - D_2)$. If $B_a$ represent the flux density in the armature behind the teeth, in kilolines per square inch, we have:

$$B_a = \frac{10^3 \phi}{\lambda (D_1 - D_2) K^{IX}} \tag{36}$$

Whence,

$$(D_1 - D_2) = \frac{10^3 \phi}{\lambda B_a K^{IX}} \tag{37}$$

Also

$$D_1 + D_2) = (D_1 - D_2) + 2 D_2 = \frac{10^3 \phi}{\lambda B_a K^{IX}} + 2 D_2 \tag{38}$$

But

$$D_2 = \frac{\tau p}{\pi} \tag{39}$$

Combining (18) and (39),

$$D_2 = \frac{\lambda p}{K^{IV} \pi} \tag{40}$$

Combining (35), (37), (38) and (40),

$$W_{ai} = 220 \frac{\phi}{B_a} \left( \frac{10^3 \phi}{B_a \lambda K^{IX}} + \frac{2 \lambda p}{K^{IV} \pi} \right) \tag{41}$$

Substituting for $\lambda$ from equation (20),

$$W_{ai} = \left\{ \frac{22000}{B_a} \sqrt{\frac{K^{II} K B_p}{10 \sigma}} \left( \frac{1}{B_a K^{IX}} + \frac{.636 p \sigma}{K^{IV} K^{II} K B_p} \right) \right\} \phi^{\frac{3}{2}} \tag{42}$$

And

$$W_{ai} = K^{X} \phi^{\frac{3}{2}} \tag{43}$$

where $K^{X}$ is the expression in the brace in equation (42).

The weight of armature active iron as expressed in (42), should, of course, be multiplied by a factor to allow for the weight of teeth and unavoidable scrap previously referred to. If $p_{ai}$ represent the price, in dollars per pound, of the iron used in the armature, then the cost of armature iron $S_{ai}$ will be:

$$S_{ai} = p_{ai} K^{X} \phi^{\frac{3}{2}} \tag{44}$$

Even in the so-called "copper machine," the cost of armature active iron is usually as great as that of the armature copper, and in most cases is slightly greater. As we depart from the "copper machine" and approach the "iron machine," the armature active iron increases very rapidly, as shown by the above equation; and this partially accounts for the fact that the "iron machine" compares unfavorably in cost with the "copper machine".

## THE YOKE.

Although the mechanical design of alternator yokes has undergone many changes, the writer has been able, by comparing the weights of consistently designed yokes, to obtain an equation which will give the weight within about 15 per cent. The yokes considered for obtaining the equation belonged to a line of alternators, the bores of which were from 25 to 250 inches, and whose pole lengths were from 6 to 20 inches. They were all of modern, open type, and the material used in them was cast iron. The equation is:

$$W_y = K^{\mathrm{XI}} D_1^{\frac{3}{2}} \lambda^{\frac{1}{2}} \tag{45}$$

$W_y$ is the weight of the yoke in pounds, $D_1$ the outside diameter of the stator laminations in inches, $\lambda$ the length of pole parallel to the shaft, and $K^{\mathrm{XI}}$ a coefficient whose value lies between 1.2 and 3, the exact value depending upon the design adopted. $K^{\mathrm{XI}}$ had nearly the same value for the yokes considered for obtaining the equation. The extreme values are for yokes which were very light or very heavy.

From equations (37), (39) and (18) we have

$$D_1 = D_2 + (D_1 - D_2) = \frac{\lambda p}{K^{\mathrm{IV}} \pi} + \frac{10^8 \phi}{\lambda B_a K^{\mathrm{IX}}} \tag{46}$$

Hence

$$W_y = K^{\mathrm{XI}} \lambda^{\frac{1}{2}} \left[\frac{\lambda p}{K^{\mathrm{IV}} \pi} + \frac{10^8 \phi}{\lambda B_a K^{\mathrm{IX}}}\right]^{\frac{3}{2}} \tag{47}$$

In expanding the above binomial, it is unnecessary for our purposes to consider more than two terms in the series; since, except for very small diameter machines, the first term in the binomial is considerably greater than the second; and secondly, the fourth term of the series is negative and nearly cancels the positive third, the negative sixth term nearly cancels the positive fifth, etc. We have then, after expanding,

$$W_y = K^{\text{XI}}\,\lambda^{\frac{1}{2}}\left[\left(\frac{\lambda\,p}{K^{\text{IV}}\,\pi}\right)^{\frac{3}{2}}+\frac{3}{2}\left(\frac{\lambda\,p}{K^{\text{IV}}\,\pi}\right)^{\frac{1}{2}}\frac{10^3\,\phi}{B_a\,K^{\text{IX}}\,\lambda}\right] \tag{48}$$

Substituting for $\lambda$ from (20) and simplifying,

$$W_y = \left\{565\,K^{\text{XI}}\sqrt{\frac{p}{K^{\text{IV}}}}\left[\frac{.318\,\sigma\,p}{K\,K^{\text{II}}\,K^{\text{IV}}\,B_p}+\frac{1.5}{K^{\text{IX}}\,B_a}\right]\right\}\phi \tag{49}$$

And

$$W_y = K^{\text{XII}}\,\phi \tag{50}$$

where $K^{\text{XII}}$ is the expression in the brace in (49).

If $p_y$ represent the price of material used in the yoke in dollars per pound, and $S_y$ the cost of material required for the yoke, then

$$S_y = p_y\,K^{\text{XII}}\,\phi \tag{51}$$

In order to allow for the errors introduced by neglecting the depth of the stator teeth, and by discarding all but the first two terms in the series after expanding the binominal, the value of $K^{\text{XII}}$ should be increased by about 15 per cent.

## POLES.

The radial height, $H$, of the pole evidently must depend upon the number of ampere turns required on full field. As previously pointed out, the full field ampere turns are proportional to the armature ampere-conductors per pole, and these latter are equal to the product of the pole pitch and ampere conductors per inch (see equation 5). Since the pole waist, $W$, must also be nearly proportional to the pole pitch, $H$ should increase in some definite relation with $W$. Comparing the dimensions of a large number of poles for consistently designed alternators having single layer edge-wound fields, the writer has found the following relation to hold:

$$H = K^{\text{XIII}}\sqrt{W} \tag{52}$$

$K^{\text{XIII}}$ lies between 2.5 and 4.5, depending upon the number of ampere conductors per inch; and the designer who has the data of a large number of alternators at his command, can readily determine the best value for this coefficient. $H$ includes the radial dimension of the pole head, the projections of which are used for holding the field copper in place when the alternator is in operation; it does not include the radial dimension of the dove-tail, if dove-tails be used for fastening the poles to the field ring. If the projections of the pole head be neglected in comparison with the remainder of the pole, we may write as the weight $W_p$ of the poles in pounds:

$$W_p = 0.28\, p\, W\, K\, \lambda\, H \tag{53}$$

Substituting for $W$ from (12), for $H$ from (52) and for $\lambda$ from (20), we have:

$$W_p = \left\{ 1580\, p\, K^{xiii} \left(\frac{K^{ii}}{K}\right)^{\frac{1}{4}} \left(\frac{\sigma}{B_p}\right)^{\frac{5}{4}} \right\} \phi^{\frac{5}{4}} \tag{54}$$

And $$W_p = K^{xiv}\, \phi^{\frac{5}{4}} \tag{55}$$

where $K^{xiv}$ is the expression in the brace in (54).

Representing by $p_p$ the price, in dollars per pound, of the iron used in the poles, and by $S_p$ the cost of material for the poles, we have:

$$S_p = p_p\, K^{xiv}\, \phi^{\frac{5}{4}} \tag{56}$$

$K^{xiv}$ should be increased by some percentage to allow for the pole tips (which were neglected in the derivation of the equation), and for the scrap material.

## FIELD RING.

In the following derivation, it is assumed that if the field ring be made sufficiently large to carry the flux (allowing for poor material, blow holes, etc.), it will be large enough for mechanical purposes. This is usually the case, although it occasionally happens that it is necessary to make the field ring heavier for mechanical reasons than would be demanded for electrical purposes.

Considering the field ring to be solid and of the same axial length as the pole, we have as its weight:

$$W_{f.r.} = .28 \times \frac{\pi}{4}\, \lambda\, (d_1^2 - d_2^2) = .22\, \lambda\, (d_1 - d_2)\, (d_1 + d_2) \tag{57}$$

But

$$(d_1 - d_2) = \frac{10^8\, \phi\, \sigma}{B_{f.r.}\, \lambda} \tag{58}$$

And $$(d_1 + d_2) = 2\, d_1 - (d_1 - d_2) \tag{59}$$

From (39) and (52)

$$d_1 = D_2 - 2\, H = \frac{\tau\, p}{\pi} - 2\, K^{\text{xiii}} \sqrt{W} \tag{60}$$

Combining (12), (18), (59) and (60),

$$(d_1 + d_2) = \frac{2\, \lambda\, p}{\pi\, K^{\text{iv}}} - 4\, K^{\text{xiii}} \sqrt{K^{\text{ii}}\, \lambda} - \frac{10^8\, \phi\, \sigma'}{B_{f.r.}\, \lambda} \tag{61}$$

Substituting (58) and (61) in (57)

$$W_{f.r.} = .22 \left(\frac{10^8 \phi\, \sigma'}{B_{f.r.}}\right) \left(\frac{2\, \lambda\, p}{\pi\, K^{\text{iv}}} - 4\, K^{\text{xiii}} \sqrt{K^{\text{ii}}\, \lambda} - \frac{10^8\, \phi\, \sigma'}{B_{f.r.}\, \lambda}\right) \tag{62}$$

Substituting for $\lambda$ from (20),

$$W_{f.r.} = \left\{ \frac{4450\, \sigma'}{B_{f.r.}} \sqrt{\frac{K\, K^{\text{ii}}\, B_p}{\sigma}} \left( \frac{p\, \sigma}{K\, K^{\text{ii}}\, K^{\text{iv}}\, B_p} - \frac{1.57\, \sigma'}{B_{f.r.}} \right) \right\} \phi^{\frac{3}{2}} -$$

$$\left\{ \frac{4900\, \sigma'}{B_{f.r.}} K^{\text{xiii}} \left( \frac{\sigma\, K^{\text{ii}}}{K\, B_p} \right)^{\frac{1}{4}} \right\} \phi^{\frac{5}{4}} \tag{63}$$

And $$W_{f.r.} = K^{\text{xv}}\, \phi^{\frac{3}{2}} - K^{\text{xvi}}\, \phi^{\frac{5}{4}} \tag{64}$$

where $K^{\text{xv}}$ and $K^{\text{xvi}}$ are respectively the first and second expressions in braces in (63).

Representing by $p_{f.r.}$ the price in dollars per pound of the field ring material, and by $S_{f.r.}$ the cost of the field ring, we have:

$$S_{f.r.} = p_{f.r.}\, K^{\text{xv}}\, \phi^{\frac{3}{2}} - p_{f.r.}\, K^{\text{xvi}}\, \phi^{\frac{5}{4}} \tag{65}$$

$K^{\text{xv}}$ and $K^{\text{xvi}}$ should be increased by some percentage to allow for the spider arms, the weight of which will depend somewhat upon the flux.

## COLLECTION OF TERMS FOR THE FINAL EQUATION.

Summing up the costs of material required for the principal parts of the alternator, we have

$$S_m = S_f + S_a + S_{ai} + S_y + S_p + S_{f.r.} \tag{66}$$

$$= p_f\, K^{\mathrm{v}} \frac{1}{\phi} + p_a\, K^{\mathrm{viii}} \frac{1}{\phi^2} + p_{ai}\, K^{\mathrm{x}}\, \phi^{\frac{3}{2}} + p_y\, K^{\mathrm{xii}}\, \phi + p_p\, K^{\mathrm{xiv}}\, \phi^{\frac{5}{4}}$$

$$+ p_{f.r.}\, K^{\mathrm{xv}}\, \phi^{\frac{3}{2}} - p_{f.r.}\, K^{\mathrm{xvi}}\, \phi^{\frac{5}{4}} \tag{67}$$

Each of the terms in the right-hand member of equation (67) should be multiplied by some factor to allow for the unavoidable scrap and for parts which are not allowed for in the equation, such as the stator teeth, the pole tips, the spider arms, etc.

Rewriting equation (67), we have:

$$S_m = p_f\, K^{\mathrm{v}} \frac{1}{\phi} + p_a\, K^{\mathrm{viii}} \frac{1}{\phi^2} + (p_{ai}\, K^{\mathrm{x}} + p_{f.r.}\, K^{\mathrm{xv}})\, \phi^{\frac{3}{2}} + p_y K^{\mathrm{xii}}\, \phi$$

$$+ (p_p\, K^{\mathrm{xiv}} - p_{f.r.}\, K^{\mathrm{xvi}})\, \phi^{\frac{5}{4}} \tag{68}$$

Or

$$S_m = \alpha_1 \frac{1}{\phi} + \alpha\, \frac{1}{\phi^2} + \alpha_3\, \phi^{\frac{3}{2}} + \alpha_4\, \phi + \alpha_5\, \phi^{\frac{5}{4}} \tag{69}$$

where $\alpha_1$, $\alpha_2$, etc., are respectively $p_f$, $K^{\mathrm{v}}$, $p_a\, K^{\mathrm{viii}}$, etc.

Differentiating equation (69) with respect to $\phi$, we have:

$$\frac{d\, S_m}{d\, \phi} = -\frac{\alpha_1}{\phi^2} - \frac{2\, \alpha_2}{\phi^3} + \frac{3}{2}\, \alpha_3\, \phi^{\frac{1}{2}} + \alpha_4 + \frac{5}{4}\, \alpha_5\, \phi^{\frac{1}{4}} \tag{70}$$

$S_m$ will be a minimum when $\frac{d\, S_m}{d\, \phi} = 0$; hence, after clearing we have:

$$\frac{3}{2} \alpha_3\, \phi^{\frac{7}{2}} + \alpha_4\, \phi^3 + \frac{5}{4}\, \alpha_5\, \phi^{\frac{13}{4}} - \alpha_1\, \phi - 2\, \alpha_2 = 0 \tag{71}$$

This equation is of such high degree that, as well as the writer has been able to determine, it can be solved only by trial. However, after having determined the values of the various constants, the writer has been able to find that value of

$\phi$ which will satisfy the equation in two or three trials, requiring from three to five minutes. Equation (71) is used in determining that value of flux to employ to obtain the most economical use of material. The algebraic values of the constants occurring in equation (71) will be found in the notation.

### EXAMPLE OF THE APPLICATION OF THE WRITER'S METHOD.

Design of an 800-kw. at 85% power-factor, 480 volts, three-phase, 60-cycle, 360 rev. per min. alternator to meet the following specifications:

*Regulation.* Rise in voltage with 800-kw. load, 100% power-factor shall not exceed 8% above normal, speed and excitation remaining constant. Rise in voltage with 800-kw. load, at 85% power-factor, shall not exceed 22% above normal, speed and excitation remaining constant.

*Heating.* After operating for 24 hours with 800 kw. load at 85% power-factor, the temperature rise shall not exceed 35° cent. in any part. After operating for two hours following the full-load run, with a load 25% above full load at 85% power-factor, the temperature rise shall not exceed 45° cent. in any part.

*Efficiency.* With 85% power-factor, the generator will have an efficiency not less than 93.5% at full load; 92.2% at 0.75 load; 89.5% at 0.50 load. Friction and windage to be included in the losses.

*Excitation.* The excitation will be at 120 volts. The excitation will not exceed 125 amperes when the generator yields its full load at 100% power-factor; the excitation will not exceed 180 amperes when the generator yields its full load in kilowatts at 85% power-factor.

The generator is to be capable of delivering its normal voltage of 480 when operated at 25% overload in kilowatts at 85% power-factor.

The generator must be able to stand an overspeed of 50%.

In accordance with the above specifications, the generator will have an output of 942 kilovolt-amperes, and will have 20 poles. We shall assume that if the field ring be made of cast steel, and large enough to carry the flux, it will be sufficiently strong to stand the 50% overspeed. This will be checked after the machine is designed.

As the voltage is low, the armature conductor will be large, and there will be an eddy-current loss in the copper. We shall therefore take $K^{VI} = 3.5 \times 10^4$, and $T = 30°$, allowing a margin of 5 degrees.

The alternator must have sufficient field margin to give its voltage with 25% overload in kilowatts at 85% power-factor. We shall, therefore, take $K' = 1.8$. We shall assume 23.5 kw. excitation on full field, this being 2.5% of the output of the alternator. We shall then be able to meet the excitation guarantees.

We shall assume the following values for the quantities in the equations:

$B_a = 33$; $B_{f.r.} = 63$; $B_p = 97$; $k = .96$; $K = .92$; $K' = 1.8$; $K^{\text{II}} = .45$; $K^{\text{III}} = .85$; $K^{\text{IV}} = 1$; $K^{\text{VI}} = 3.5 \times 10^4$; $K^{\text{VII}} = 3.7$; $K^{\text{IX}} = .81$; $K^{\text{XI}} = 1.9$; $K^{\text{XIII}} = 2.5$; $p = 20$; $p_a = .23$; $p_{ai} = .037$; $p_f = .2$; $p_{f.r.} = .036$; $p_p = .028$; $p_y = .025$; $P_a = 942$; $P_f = 23.5$; $T = 30$; $\sigma = 1.2$; $\sigma' = 1.28$; $\sim = 60$.

Substituting the above values, we obtain the following:

$K^{\text{V}} = 6300$; $K^{\text{VIII}} = 23{,}000$; $K^{\text{X}} = 510$; $K^{\text{XII}} = 1180$; $K^{\text{XIV}} = 380$; $K^{\text{XV}} = 354$; $K^{\text{XVI}} = 99$.

We shall increase the value of these factors by the following percentages to allow for scrap and parts not included:

Field copper ($K^{\text{V}}$) 0%; armature copper ($K^{\text{VIII}}$) 15%; armature laminations ($K^{\text{X}}$) 70%; poles ($K^{\text{XIV}}$) 25%; yoke ($K^{\text{XII}}$) 15%; field ring ($K^{\text{XV}}$ and $K^{\text{XVI}}$) 15%.

Substituting in equation (71), we obtain

$$69\,\phi^{\frac{7}{3}} + 34\,\phi^{3} + 11.5\,\phi^{\frac{13}{4}} - 1260\,\phi - 12{,}200 = 0$$

from which we find by trial that $\phi = 4.5$ megalines per pole.

We wish to build a machine that can be wound for either two or three phase, and for voltages at least as high as 2300, in order that the alternator "carcass" may be useful in the future. The first of these requirements necessitates a number of slots per pole which will be a multiple of 6. If we use 12 slots per pole, they will be rather narrow, and we must have twice as many coils as by using 6 slots, resulting in a great deal more labor. Moreover, the die work for the 12-slot punching would be considerably greater. On the other hand, for the same weight of material, the heating with the 12-slot punching would be slightly less and the wave-form slightly better. We shall, however, decide in favor of 6 slots per pole. With $\phi = 4.5$, we shall require 1.2 conductors per slot with Y connection, or 2.07 with delta connection. Using 2 conductors per slot, and connecting delta, we find that $\phi = 4.66$, which we shall adopt.

In order to find the diameter and length, we shall use equation (20) as a trial, and find $\lambda = 11.8$ inches. From (18) and (39) we find that $D_2 = 75$ in., giving a pole pitch of 11.8 inches, and a peripheral speed at the bore of 7100 ft. per minute. With this diameter we shall have 670 ampere conductors per inch.

We shall take the length of the pole $\lambda$ to be 12 in. Taking the axial length of the armature to be 13.5 in., including two 0.5-in. outside, ventilating ducts, and allowing for three other 0.5-in. vents, the gross iron will be 11 in. and the net iron 9.7 in. Allowing for four teeth through which the flux will pass, and a tooth density of 98 kilolines per square inch, the tooth width will be 1.22 in. This will give a slot width of 0.75 in.

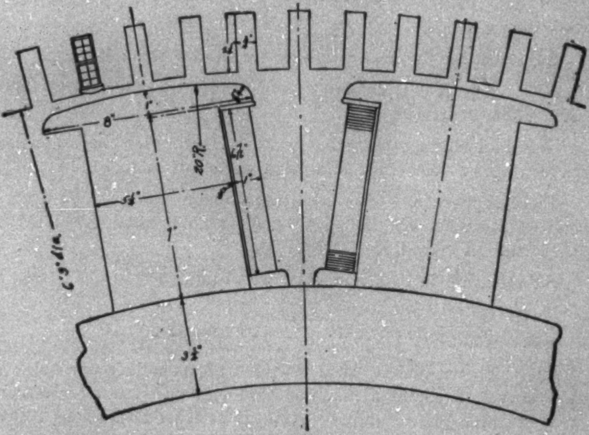

FIG. 1.

In order to reduce the eddy-current loss in the armature conductors to a minimum, we will use a double layer wave winding and laminate the conductor by using square double cotton covered wire. Two number 2 square B. & S. fit nicely in width, and allowing for three in depth in the half slot, we obtain a current density of 1670 amperes per square inch. Allowing for the stick and for insulation, we shall make the slot depth 2.25 in. Conforming with our assumed density of 33 kilolines per square inch in the armature core, we shall make the depth behind the teeth 7.25 in., corresponding to a density of 33.2.

As the pole length $\lambda$ is 12 in., we find from equation (3) that $W$, the pole "waist", is 5.25 in. With a 1 in. width of strip, the mean turn will be 37 in. Taking $K'$ to be 1.8, we find from equation (5) that $X = 14,200$ ampere-turns. From equation (8) we find that 0.074 square inches are required. 0.07 in.x1 in. has slightly less section, but we can find from the saturation curves which will be plotted, whether this gives sufficient margin. By winding 75.5 turns on each pole, we shall meet both the temperature and excitation guarantees. This will require a radial length of pole of 7 in. excluding the head, and allowing 1 in. for the head, gives $H = 8$ in.

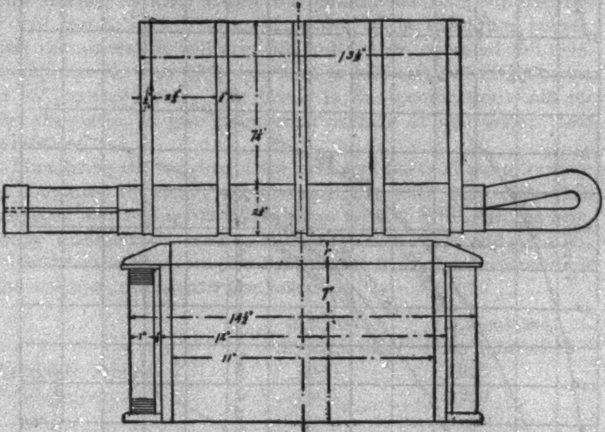

FIG. 2.

Employing cast steel for the field ring, and allowing a density of 63 kilolines per square inch, the radial depth will be 3.75 in. for an axial length of 12.5 in. Allowing 1.5 in. for the radial depth of the pole dovetail, we obtain a stress of 5200 lb. per square inch due to centrifugal force at normal speed. At 50% overspeed this will be 11,700, which is safe, as it allows a factor of safety of about 5.

In order to secure the regulation guaranteed, we shall use an air gap of 0.3 in. at the middle of the pole, making the pole eccentric with a 20 in. radius. This will make the gap ampere-turns per pole approximately 5500. The magnetic circuit of the machine is shown in Figs. 1 and 2.

The calculated saturation curves are not given, but in Fig. 3 will be found the test curves. The air-gap came a little smaller than was specified, 0.28 in. instead of 0.3 in.; but notwithstanding this discrepancy the regulation guarantees are easily met, being 7.5% and 21% with 800 kw. load and at respectively 100% and 85% power-factor. The efficiencies obtained were: full

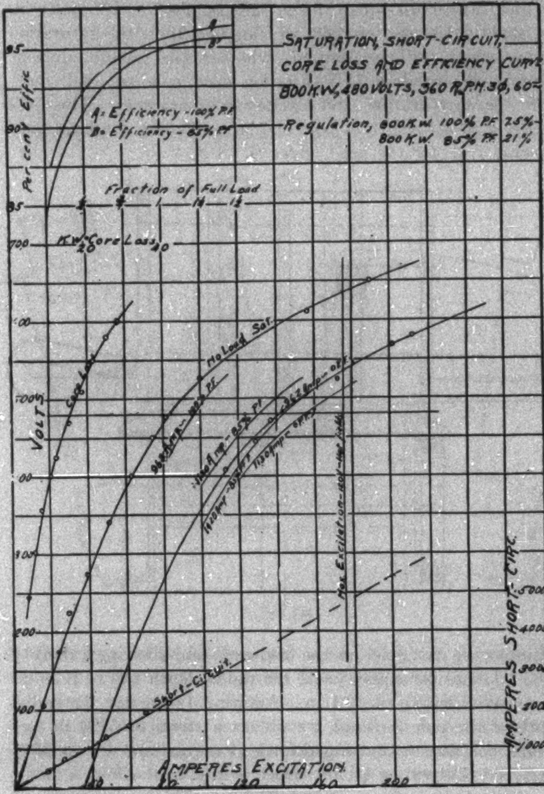

FIG. 3.

load in kilowatts, 85% power-factor, 94.72 per cent.; 0.75 load 93.54 per cent.; 0.50 load 91 per cent. The heat run showed the following results: 12 hours, 480 volts, 1005 amperes armature, 144 amperes field. Temperature rise stator iron, 22° cent.; stator coils 20° cent.; field coils 34° cent. (taken at a power-factor less than 20%). From this heat run it will be seen that the temperature rise with 800 kw. load at 85% power-factor (1130 amperes) will not exceed 25.5° cent. on the stator coils; nor will the rise exceed 40° cent. with 25% overload. As in neither case will the excitation be greater than 145 amperes, the field heating is also within the guaranteed temperature rise. It will also be seen, from an inspection of the saturation curves, that the alternator will give 535 volts when operated full field, normal speed, with 25% overload in kilowatts (1420 amperes) at 85% power-factor. The clause in the specifications calls for the alternator to give its normal voltage of 480 under these conditions.

Comparing the weights of the principal parts of the alternator as computed by means of equations (23), (33), (43), (50), (55), and (64), [employing the same value for $K^{\text{v}}$, $K^{\text{viii}}$, etc., as originally assumed ($K^{\text{v}}=6300$, $K^{\text{viii}}=23{,}000$, etc.), and $\phi=4.66$], with the calculated weights determined from the dimensions of the machine, we obtain the following:

| | Calculated by equation | | Calculated from dimensions | |
|---|---|---|---|---|
| Armature copper | 1060 | | 1020 | |
| Field copper | 1360 | | 1260 | |
| Summation copper | | 2,420 | | 2,280 |
| Armature laminations | 6400* | | 6240 | |
| Pole laminations | 2860† | | 3350 | |
| Yoke | 6300‡ | | 6300§ | |
| Field ring | 2700 | | 2300 | |
| Summation iron | | 18,260 | | 18,190 |
| Sum of iron and copper | | 20,680 | | 20,470 |

*25% added to allow for teeth.
†10% " " " " pole tips
‡15% " " " " inaccuracy of equation.
§Actual weight of rough casting.

In the above calculations involved in the design of the alternator, but one diameter and one length were considered. This was done in this case to prevent the paper becoming too lengthy.

The alternator as above designed well illustrates the application of the writer's method to an actual example. In an alternator for this rating it is possible to secure the same electrical characteristics by approaching either the copper or iron machine, increasing the air-gap and possibly the flux density in the poles in the former, to secure regulation. Had the circulation of air been increased, thereby reducing the heating for the same weight of copper, and had the densities and other constants in the equations remained the same, the equation would have indicated a nearer approach to the copper machine. However, in a case of this kind it might be advantageous to increase the flux densities in the armature. It will therefore be seen that the evaluation of many quantities entering into the equations must depend upon the judgment of the designer.

## APPENDIX.

As was noted in the paragraph following equation (21), other things being equal, the product of the weight of the field copper and the kilowatts excitation is constant. If, as is often the case, there is no limit placed by the field becoming crowded near the bases of the poles, or by field heating, the designer may have some difficulty in deciding upon the best value to assign to the excitation. He may overcome this difficulty if his chief aim is to reduce to a minimum the cost of the entire equipment, including alternator and exciter, by bringing the cost of the exciter into the equations, as is carried out in the following derivation:

Rewriting equation (21),

$$W_f P_f = \gamma \frac{1}{\phi} \tag{72}$$

where $\gamma$ = expression in the brace in equation (21); that is,

$$\gamma = \frac{3130\, K^{\text{III}}\, \sigma}{K\, B_p} \; \frac{(K^{\text{II}} + 1)^2}{K^{\text{II}}} \; \left[\frac{P_a\, K^{\text{I}}}{\sim k}\right]^2$$

If $S_e$ represent the cost, in dollars, of the field copper plus the cost of the exciter, and $p_e$ the cost in dollars per kilowatt of the exciter, we have:

$$S_e = p_e P_f + p_f W_f \tag{73}$$

$$= p_e P_f + p_f \frac{\gamma}{\phi P_f} \tag{74}$$

In order that $S_e$ be a minimum, $\frac{d S_e}{d P_f} = 0$, hence:

$$\frac{d S_e}{d P_f} = p_e - \frac{p_f \gamma}{\phi P_f^2} = 0$$

Whence

$$P_f = \sqrt{\frac{p_f \gamma}{p_e \phi}} \tag{75}$$

Substituting this value of $P_f$ in (72),

$$W_f = \sqrt{\frac{p_e \gamma}{p_f \phi}} \tag{76}$$

The cost of the field copper will be:

$$S_f = p_f W_f = (\sqrt{p_f\, p_e\, \gamma}) \frac{1}{\phi^{\frac{1}{2}}} \tag{77}$$

The cost of material in the principal parts of the alternator will then be:

$$S_m = (\sqrt{p_f\, p_e\, \gamma}) \frac{1}{\phi^{\frac{1}{2}}} + p_a K^{\text{VIII}} \frac{1}{\phi^2} + (p_{ai} K^{\text{X}} + p_{f.r.} K^{\text{XV}}) \phi^{\frac{3}{2}} +$$

$$p_y K^{\text{XII}} \phi + (p_p K^{\text{XIV}} - p_{f.r.} K^{\text{XVI}}) \phi^{\frac{5}{4}} \tag{78}$$

Letting $\alpha_6 = \sqrt{p_f\, p_e\, \gamma}$, we have, after differentiating with respect to $\phi$, equating to zero and clearing:

$$\tfrac{3}{2} \alpha_3 \phi^{\frac{7}{2}} + \alpha_4 \phi^3 + \tfrac{5}{4} \alpha_5 \phi^{\frac{13}{4}} - \tfrac{1}{2} \alpha_6 \phi^{\frac{3}{2}} - 2 \alpha_2 = 0 \tag{79}$$

Applying the above to the 800 kw. alternator, the design of which was outlined in the conclusion of the paper, and allowing $p_e$ = \$20.00, the evaluation of the other quantities being the same as previously,

$$\alpha_6 = \sqrt{.2 \times 20 \times 148{,}000} = 770.$$

Equation (79) becomes:

$$69\,\phi^{\frac{7}{3}} + 34\,\phi^{3} + 11.5\,\phi^{\frac{13}{3}} - 385\,\phi^{\frac{4}{3}} - 12{,}200 = 0$$

Whence $\phi$ = 4.34 megalines per pole. This value is slightly less than that given by equation (71), this latter being 4.5 megalines. The exciter kilowatts will also be somewhat less than assumed for carrying out the design of the alternator, being 18.5, as obtained from equation (75), as compared with 23.5 kilowatts assumed.

## DISCUSSION ON "THE RELATIVE PROPORTIONS OF COPPER AND IRON IN ALTERNATORS." ATLANTIC CITY, N. J. JULY 2, 1908

**W. L. Waters:** Mr. Fechheimer is to be congratulated on the success obtained in his attempts to reduce the design of alternators to a series of mathematical formulas. A good many attempts have been made in the past to reduce electrical machine design to an exact science, but they have met with little success. The first attempt was made in regard to transformer design, when rules for the most economical dimensions were formulated by various engineers, but even in this extremely simple case such rules met with very little success. I think that such attempts only serve to emphasize the well-known statement that electrical machine design is an art and not an exact science.

In the case of an alternator, there are many variables, such as voltage, speed, and frequency, which make radically different designs necessary, and these different designs may again introduce further complications in regard to cooling and windage of the machine. This being the case, it is not surprising that Mr. Fechheimer finds such extreme variations in his constants.

I think this paper is more useful in an academic way than as an assistance in practical designing. The probability is that for practical commercial designing we shall find it necessary to keep to our old method of trial and error, basing our designs and changes in design on past experience. Mr. Fechheimer will no doubt find that so much latitude must be allowed in fixing his constants that his method will in the end practically amount to a trial and error method, similar to that which has been in use for the last fifteen years.

**Comfort A. Adams:** While there is undoubtedly much truth in what Mr. Waters says, there is, on the other hand, no doubt as to the very great usefulness of a general analysis of design problems carried out as indicated in Mr. Fechheimer's paper. This is particularly true in the case of a new line of machines where the limitations introduced by the necessity of employing old frames or stampings are absent; but even in many other cases the general analysis reduces the amount of the cut-and-try process and renders the work of design more rational. Designing engineers are too much inclined to assume, because their machines operate satisfactorily and are reasonably successful commercially, that they cannot be improved. That this is far from true in many cases would, I feel sure, be made clear by the application of just such methods of analysis to machines which are the results of years of the cut-and-try process. Of course, as Mr. Waters intimates, a vast amount of practical experience and judgment is necessary to produce a good commercial piece of apparatus; but can there be any doubt that the more rational, scientific, theoretical, general analysis of this sort, when illumined by the same experience and judgment, will give better results than the experience and judgment alone? The claim often made by the practical designing engineer that he has no time for such careful theoretical analyses can hardly be upheld by experience. To me, the obvious fact is that the designing engineer cannot afford to omit the consideration of any point of view which tends to make nearer perfect the product of his work. Who has not had the experience of pushing through a hurry-up job, only to find that the saving of a few hours or even of a few days has cost the customer weeks or months of delay and consequent loss, and the manufacturer heavy financial loss, due to changes made in the finished product which might have been made in the design.

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# THE NEW METHOD OF TRAINING ENGINEERS

BY MAGNUS W. ALEXANDER

A century ago higher education in American colleges and universities aimed primarily to develop a man for the professional life of a preacher, a doctor, a lawyer, a teacher, a writer, or a philosopher. Colleges and universities responded to the demands of the life of that time. A college bred man occasionally, from choice or through circumstances, entered business activities, but the direction of the commerce and industry of the country rested chiefly with those who had worked their way up to important positions through all the steps of practical commercial and industrial life. The advantages of the broad culture and of the power of observing and reasoning, secured and developed in institutions of higher learning, were very little recognized in commercial and industrial work; and the mathematical and physical knowledge with which the colleges equipped their graduates found comparatively little call in the business activities.

The invention of the steam engine ushered in the wonderful industrial development of the world, strikingly manifested in the extensive building of steam railroad systems all over the country. This activity, requiring the construction of locomotives and rolling stock, called also for the surveying of land, the building of roadbeds, the spanning of rivers and valleys by bridges and viaducts, the leveling of hills, and the tunneling of mountains. A fair knowledge of the mathematical and physical sciences became a prerequisite of the equipment of the men who were to take charge of this kind of work. Colleges and universities, wisely then began to pay particular attention to the teaching of mathematics and physics, which were expanded until they became part of special courses devoted to instruction in civil engineering. The further development of the industries through added inventions and the extended use of machinery reacted on the colleges in demanding of some of the graduates an enlarged engineering knowledge that became an important factor in the various industrial activities. This call of the industries led to the establishment of mechanical engineering courses in many of the colleges, finally resulting in distinctive technological schools for the teaching of the various branches of the then known engineering sciences. At first, most of the graduates of the scientific courses and technological schools devoted themselves to the teaching of the sciences; or entered practical industrial life, in positions connected with railroad systems where a knowledge of civil engineering was required. Those who went into the workshops, however, found it necessary to acquire a knowledge of industrial processes and the art of the application of the sciences to the practical problems of the factory before they could assume responsible positions; and they even found that their college training worked rather against than for securing an opportunity of studying the practical side of industrial life.

A further marked change in the relation of the colleges to the industries became apparent some twenty-five years ago when electricity began to play an active part in daily life. The call for college men who had received a thorough training in the mathematical and physical sciences underlying electrical engineering now grew imperative, as such men were needed in the designing of electrical apparatus and in its manufacture, as well as in the technical management of electric street railways which were replacing the old transportation methods. Many colleges responded to this new demand by the establishment of electrical engineering courses. The rapidly changing conditions of the electrical industry, on the one hand, required the colleges to watch closely the practical applications of electrical engineering theories in the factories, and the remarkable development of new theories in college laboratories, on the other hand, obliged the manufacturers to keep in close touch with the work in the colleges. These conditions brought about a greater coöperation between engineering colleges and technical industries than had ever been the case before; and with this, grew the interdependence of the two institutions.

Graduates of electrical engineering courses more than any other engineering graduates felt the necessity of securing a good deal of the practical side of their profession in the workshops before they could become effective economic units in an industrial organization. The electrical industry had called into play many new processes of manufacture with which the student was not made familiar at college, nor had he even that general knowledge in regard to them which most young men acquire as boys in regard to ordinary mechanical processes, either by observation or by actual contact with the work. Realizing the gap between the theory of the college and the practice of the industry, some colleges added courses in practical shop and field work to their curricula. They established and maintained college work shops for that purpose.

The machine equipment and manufacturing methods of to-day soon become those of yesterday. This applies especially to colleges which neither have the resources to keep their equipment up-to-date, except at comparatively long intervals, nor for obvious reasons, can adjust their processes and methods quickly to the rapidly changing industrial conditions. Many of the men in charge of the practical shop courses, to be sure, are taken from practical life, but even they find it difficult to keep abreast of the development in the industries.

While this process of adjustment on the part of the colleges to the new industrial life was going on, manufacturers of steam engines, locomotives and similar devices, and especially manufacturers of electrical apparatus, evolved their own methods through which the college education of the young man was rounded out by practical experience in the industry before he could be placed even in a minor position of responsibility. These "student courses" proved very valuable from the beginning, and became so important that in most cases they were placed under the supervision of men especially selected for the training of students. The general aim was to give the student an opportunity during a two years' course, to apply the theories learned at college to the practical problems of daily industrial life, to acquaint him with factory conditions, and, as far as time would permit, with some of the factory processes; he was usually required to work regular factory hours and to submit in general to the rules governing the conduct of men in the shop.

With all due recognition of the excellent systems for training college graduates that have been developed in many establishments throughout the country, it may not be amiss to outline here briefly the system that was evolved a few years ago by the General Electric Company in the Works at Lynn, Mass., where the effort for a well conceived and well conducted student course has resulted in a system of recognized efficiency. The student course at Lynn is planned to meet the requirements of the General Electric Company for designing and estimating, construction and commercial engineers, and technical salesmen. The company takes graduates of technical schools and trains them during a period of two years, giving them during this time practical experience in the handling and testing of apparatus, in order to fix in the students' minds the practical application of engineering theories, to enlarge their engineering knowledge in general, to acquaint them with the competitive value of the product of the factory, and to develop them along lines of their future usefulness to the company.

In order that each student might receive careful individual attention thereby directing him into the field of his greatest capacity, a supervisory committee was organized a few years ago, consisting of four members of the engineering corps of the Lynn Works, one being the superintendent of the testing department. The committee meets either weekly or fortnightly. Each new student is called before the committee sometime during his first three months of service with the company in order that the committee may get acquainted with him and he with the committee. He is questioned as to his future plans and is advised as to the best way of carrying them out. Proper record of the student and his aims and of the impression that he has made on the committee is kept in the minutes of the meeting, to be referred to again when the student is called the second time within the next six months. He is then examined quite fully with regard to his theoretical and applied technical knowledge, his alertness in following up the applications of engineering theories and in taking advantage of the educational facilities offered by the course. The examination is of a more or less informal character, but of eminently practical value; it does not aim to find fault with the student but rather to assist him in his work and point out to him the way to success.

As a rule, the young man is not asked to recite theories and formulas, but is rather tested as to his power of comprehension in explaining the reasons for certain actions in engineering work. A question as to whether a constant current transformer should be short-circuited or open-circuited so as to protect the station equipment, if in case of an emergency quick action in the power house is imperative, will bring out more truly the student's real knowledge of transformer design than any question as to the theory of transformers; it will also give a clue to the student's mental alertness and his ability to think for himself. Similarly, a question as to the proper apparatus for lighting a city under stated conditions or as to the reasons for the superiority of certain motors over those of competitors will open an almost unlimited field for testing the student's engineering knowledge, his understanding of electrical apparatus, and his native ability as a technical salesman. These examinations are repeated two or three times during the student course. Those who do not come up to the standard, after they have been warned by the committee, are dropped from the course. Those who give a satisfactory account of themselves are usually placed in suitable positions as soon as they graduate from the course.

The efforts of the supervisory committee have resulted in encouraging the students in their work and in giving the company a fair idea of the value of each candidate for an engineering position. This system has also stimulated in the students a desire for increased engineering knowledge which has manifested itself in the formation of students' clubs to compare notes and to discuss the various problems. It has even led to the publication by two students of a very interesting booklet on " Questions and Answers about Electrical Apparatus ", a valuable aid to the young men in the course. The members of the committee, on the other hand, have been kept informed, through close contact with the students, of many matters with which they would not have otherwise become familiar, on account of the complexity of the company's business, and some of the ideas advanced by students have led the committee to adopt methods which have proved of advantage to the students and to the company.

As a member of this supervisory committee, I have had an unusual opportunity to study at close range several hundred of the graduates of technical schools, and to follow their early careers as junior engineers in various positions with the company. Although the present system of engineering training possesses many points of merit and has turned out engineers of high rank, nevertheless I have become convinced that this combination of four years of mental activity in college with two subsequent years of practical shop work in the student course, calling for physical exercise to a large extent, is not the most effective method of training designing, commercial, and construction engineers. It fails to give that insight into the practical side of electrical engineering and into the proper relation of the economic forces of an industrial organization that is more and more demanded of those who wish to take leading positions in the industrial field. Moreover, the atmosphere at college is charged with little of the seriousness of business. The correlation of theory and practice is not sufficiently close to facilitate the proper appreciation of the sciences in their concrete applications. While shop practice courses at college endeavor to approximate the desired condition, it must be admitted that they can give at best only a faint idea of the real industrial situation. The truth of this statement will be readily admitted by those who have employed many college graduates in engineering positions and have followed rather closely their early careers as engineers. The college has initiated the young men only in a very general way into the practical processes, and has given them but a speaking acquaintance with machines and materials; of course, hardly more can be expected of the colleges in view of their limited equipment and the brief time available for this purpose. Moreover, consideration of the elements of time and money in carrying out practical work is entirely neglected at college, although the proper appreciation of economic values is the important factor that makes for success in industrial life. Only extended experience in practical work in which time and money play leading parts can instill a proper conception of these values. It is natural, therefore, that colleges leave to subsequent practical life the young men's development along these lines. Similarly, no amount of the study of political economy at college alone can give the student a true perspective of the relation of employer to employee and of the many economic and sociological phases that prove more and more perplexing in our complicated industrial system; a thorough knowledge and appreciation of these forces, however, are to-day considered essential for those who are called to positions of responsibility in the executive and administrative departments of industrial life.

A serious study of this situation has led me to believe that the best engineering education can be obtained under a plan which provides that the teaching of the theory and practice should go hand in hand, and, so far as practicable, successive steps in the one should be based on similar advances made in the other, at such intervals as to permit of the most advantageous interplay of the two; and further, that the colleges devote their whole time to the teaching of the theory for which they are so eminently adapted, leaving it to real workshops to initiate the student into practical work, for which they in turn are best equipped. From an educational standpoint, this plan should prove efficacious, for mental conception of any activity is facilitated by the physical perception of a given process, as illustrated in the whole development of the human being; and on the other hand, mental visions are more firmly clinched by concrete application. Moreover, under such a plan, the freedom enjoyed by students during the college career is happily interrupted by the stern discipline that must prevail in a business organization; the advantage of this college freedom in the development of the young man's character, in the spreading of his wings, so to speak, is not lost, but his freedom is regulated by frequently recurring intervals of discipline in the factory, so that he may be prevented from soaring to the skies in his fanciful ideas engendered by his personal irresponsibility and after four years find himself all too rudely pulled back to earth by the stern call of practical life with its demand for coöperation of all forces. This plan also trains and develops the young man in the very life to which he will devote his future efforts and gives him the love for it, which, after all, is necessary for his success. Economically this coöperative education is sound in principle, in that it will give to the industries engineers who are known to be capable of assuming responsibility and can therefore be placed in positions of leadership. An arrangement of this kind, carrying with it financial remuneration during a part of the time, will attract to engineering work young men who are mentally and physically adapted to it but who at the present time do not enter college for financial reasons or for lack of appreciation of the value of higher education. The poor boy, if otherwise fitted for it, will be given a chance to acquire a college education by "working his way" through college in activities that have a direct beneficial bearing on his future career. The influence of the college will therefore, be extended and in no way restricted by the coöperative plan as contemplated.

It is obvious that only those should be permitted to enjoy the benefits of coöperative education who can prove both their mental fitness for a college training and their adaptability to the requirements of practical work. The test, therefore, should be a successful passing of entrance examinations into an engineering school and satisfactory service during a trial period in the factory. The former should precede the latter, so that the workshop may not be put to any expense for the preliminary training of young men who could not enter upon the course on account of educational deficiency. The trial period should be of at least three months' duration, which I consider necessary for a fair judgment in regard to a young man's ability for, and right attitude toward, practical work. If properly conducted, the trial period will afford a splendid opportunity to differentiate between those who give fair promise for a successful career as engineers and those who show a lack of the essential qualifications for "making good". The coöperative course, involving as it does the expenditure of money on the part of a business organization, should of course be open only to promising young men, especially since the demand for admission to the course will undoubtedly many times exceed the available opportunities.

After passing a satisfactory educational and practical test, the young man begins a coöperative course of six years, corresponding to the six years at present occupied by the engineering college education and the factory student course. Under either plan, therefore, the junior engineer will start his life's work after the same length of preparation. The plan which I have in mind provides that the first five years be spent in alternating periods at the college and factory, leaving the sixth year to be devoted entirely to college work. Under this arrangement, coöperative students will be taught in separate classes for the first five years at college, but in their senior year, they may be merged with the regular seniors. The advantage of the latter provision lies in the opportunity which it gives to the engineering apprentice for uninterrupted attention to his thesis and original research work and for forming wider college associations by coming in contact with the larger body of regular college men. This plan has an economic value to the college and places both classes of college students on the same plane with regard to their final examinations and the attainment of their college degrees. The fact that the last year is spent away from the factory will strongly appeal to manufacturers in that those engineering apprentices who upon completion of the coöperative course enter the engineering staff of competing firms will not possess the data relating to the latest developments and experiments. For myself, I rather believe that the last year at college will be interpreted by most students as a leave of absence at the expiration of which they will gladly return to the establishment which made it possible for them to receive an engineering training, and which in turn will willingly offer adequate inducements to secure the services of those with whose special aptitudes it is familiar.

As to the length of the alternating periods during the first five years of the course, extended experience alone will be able to determine the most efficacious arrangement. We may in the meantime, however, consider various proposals, and, by the process of elimination, narrow our consideration down to the few which in the light of logical reasoning might appeal as efficient. The length of the alternating period is a very important element in this plan, for too long or too short a time may defeat the very objects which the coöperative course seeks to accomplish. In the light of the aims of the course previously advanced, short periods seem to recommend themselves to us. A year or even six months spent alternatingly at college and at the factory would, I think, fail to give that close coördination of theory and practice that is an essential feature of the plan; nor would it establish that balance between the college freedom and the factory discipline which has already been referred to as very desirable. Short periods, on the other hand, will develop that facility in the young man's physical and mental make-up that will enable him to adjust himself quickly to the interacting influence of the college and the factory. The engineering apprentice should enter upon his factory work as a college boy with all the mental alertness and the inquiring mind fostered by the college; and he should return to the college as an industrial worker with the physical energy and the determined spirit of achievement that will be developed in a hustling factory organization. The attainment of these characteristics will to a large degree determine the success of the plan. Alternating periods of a day or even a week, to take the other extreme, might keep the young man's mind in a rather chaotic state, might not give the seed sown in the class room and factory, respectively, a fair chance to take root. Such time arrangement, moreover, would seriously interfere with the best economy at the factory, and largely forfeit that sympathetic interest of the shop foremen and workmen which seems to me not only desirable but decidedly necessary. Periods of such short duration would prevent also the complete carrying out by the same men of many pieces of work which should form part of their practical education. The finishing of such work by another set of men might often entail loss of time and even spoil the work itself.

As already stated, any estimate arrived at now in regard to the length of alternating periods must be looked upon as experimental; different factory conditions might lead to different conclusions. Personally, I believe in the efficacy of an arrangement under which the periods increase in duration from the first toward the last year of the course, beginning perhaps with alternations of four or five weeks' duration and ending with time elements of college semesters. In that way, all the advantages of the coöperative course would be emphasized strongly at the beginning when they are of determining influence, and the economic consideration of the college and the factory would receive growing attention in latter years as justified by the increasing importance of the work. An important advantage under a system of alternating periods lies in the fact that one set of students can work in the shop while the other set is engaged at the college, and vice versa, thereby keeping the educational and physical equipment employed practically at all times. This plan, of course, presupposes that during the college summer vacations, all engineering apprentices will be utilized at the factory, one-half of them during the first part of the summer with a vacation following during the latter part, and the other half enjoying a rest at the close of the college year and entering upon practical work again during the middle of the summer.

It goes without saying that engineering apprentices should receive a fair compensation for services in the factory, while they would, of course, pay a tuition fee for their college training. In the latter case, they receive education from the college without giving anything in return; quite differently, however, at the factory where they receive a practical education, they make immediate returns in the commercial work which they perform. I believe, and in fact from similar experience, I know, that if the factory end of the coöperative course is well organized and efficiently conducted, an astonishing amount of good commercial work can be turned out by engineering apprentices, which will compensate fully for the wages of the apprentices and for the expenditures for special supervision, materials spoiled work, and other incidentals. Considering that the young men admitted to the coöperative course will be at least eighteen years of age, possessing a high school education and that, furthermore, they will be selected according to a rather high standard, I should advocate an initial wage which would make them entirely self-supporting while they are at the factory. Their remuneration should increase at yearly or semi-yearly intervals both to give incentive and stimulation to the young men and to keep pace with the increasing value of their work; in that way, they would also be enabled to lay up a sufficient amount for the payment of their college tuition and for other necessaries. The exact amount of the wage will, of course, depend somewhat on local conditions as to the prevailing average compensation for work and the educational and living expenditures of the particular community. As a general proposition, I might suggest a starting wage of $6 a week with a yearly increase of $2 a week, amounting therefore to $14 a week during the fifth year of the course, when the shop work ceases. On this basis, engineering apprentices would earn in the neighborhood of $1300 during the entire course as against expenditures of $600 to $1000 for the college training, according to the tuition fee prevailing at the different engineering schools.

The college as well as the industrial establishment must, of course, have the right, fully understood beforehand, to terminate the course of any engineering apprentice at any time for good reason, and discharge from one institution for unsatisfactory work or conduct must be followed by discharge from the coöperative course by the other institution. Either institution, however, may make any special arrangements with such student, and if he is transferred to the regular course at college, he should receive credit for studies already pursued.

The administration of the coöperative course would involve the appointment of a supervisory board with representation from each institution. This board would work out and supervise the details of the course of study both at the college and at the factory, and have general charge of the social and cultural needs of engineering apprentices. It would be an interesting matter to lay out a course of study which would cover the present four years' college course and at the same time lay particular stress on those subjects that may be classed under the general head of applied economics. In view of the elimination from the college course of most of the time now devoted to shop practice, mechanical drawing, and electrical testing, to which subjects the factory will give particular attention, and also on the assumption that the coördinated practical work in the shop will make it possible to cover more ground at college in a given time, it would seem that the present four years' college program could be very nearly covered in the first five years of the coöperative course. The sixth year, which is entirely spent at college, might, therefore, be devoted to thesis and research work and to special lectures both by the college instructors and by men of affairs in practical life on such subjects as business law and business organization, cost-keeping and factory accounting, the economics of production and methods of equipping and laying out of manufacturing establishments. Seminars for coöperative students in these latter subjects and in many more of a similiar character which will take the place of some of the regular fourth year subjects already covered, will prove most interesting and instructive, because practical, and the presentation and discussion of such matters by men of affairs will bring the latter into contact with the student body to the advantage of both. The supervisory board will also from time to time confer and advise with the officers of the college and the industrial establishment as to their respective work, but they shall have no authority or responsibility in regard to the work of either as long as the course is carried out in conformity with the general plan approved by both institutions.

This coöperation between the college and the industry will undoubtedly produce that kind of engineering education which will adequately meet the demands of changing industrial conditions, for engineers capable of filling executive and administrative positions. It will result in giving college instruction just as complete, thorough, broad, and cultural as in regular college courses, and a practical training in the factory infinitely more thorough and practical than can be given in any engineering college or can be obtained as advantageously in present student courses. Above all, it will produce engineers, technical in their specific knowledge, cultured in their usefulness in life's activities, sympathetic in their understanding of the aspirations and needs of men, and broad and enlightened in their conception of their own obligations as engineers and as citizens. This may sound like a very idealistic forecast, yet I fully believe in its realization under proper conditions. Furthermore, it is well that we set up for ourselves an ideal of achievement in all our work and then endeavor to approximate it as far as our own strength and circumstances will permit.

About a year and a half ago the University of Cincinnati and the manufacturers of Cincinnati arranged for a coöperative course somewhat similar to the one outlined in this paper, the principal difference being that the students at the university are spending every other week at the factory or college, respectively, and that it is contemplated to maintain this arrangement throughout the six years of the coöperative course. For reasons which I have already given, I do not agree with these features and believe that especially the short periods will give way to longer ones before the experiment has gone much further.

Manufacturers are agreed as to the advantage of interweaving theory and practice in the training of engineers, and many educators are looking in the same direction for an advance in engineering education. It is significant that a technological college of the very first rank has recently expressed willingness to establish a coöperative electrical engineering course along the lines which I have set forth in this paper, and there is good reason to believe that a very prominent concern manufacturing electrical apparatus will soon join in such an undertaking.

I trust that I have explained the advantages of the new method of training engineers in such a way as to induce action by colleges and manufacturers in various parts of the country. Members of the American Institute of Electrical Engineers, most of whom have received a college education, and are, therefore, in a position to judge the case broadly, can do a great service to the rising generation of engineers and to the industries of the country by deliberating over this problem of engineering education, so that a safe and sane policy may be adopted regarding this matter.

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# RELATION OF THE MANUFACTURING COMPANY TO THE TECHNICAL GRADUATE

BY DAVID B. RUSHMORE

Conditions in the commercial world necessitate an increasing consideration being given to the perfecting of organization and to raising the standard of individuals composing the same. The present may be said to be distinctly an age of organization, and in the competition which naturally exists, the relative efficiency attained by different organizations has much to do with their survival in the competitive struggle of modern times. Much thought is now being expended on this question and a great deal of good is resulting from the study being made of it. A whole can reach its best condition only when all of the parts which compose it are of the first class. This means that the individuals composing an organization must be of the best quality both as regards natural and acquired ability. There is an increasing demand for highly trained men, and there is considerable discussion as to what that training should be. A man who has concentrated his energies for four years on a special line of work is naturally more efficient in that line than would be possible otherwise, and consequently the properly trained college man is more efficient than the man without a college education. The ranks of industrial manufacturing concerns are, without question, becoming more largely filled with college graduates and therefore the importance of the technical graduate is increasing. There will always be men of unusual natural ability who will succeed without a college education, but such individuals undoubtedly would have been able to accomplish more if they could have had the advantages of concentrated training correctly applied for a number of consecutive years.

Manufacturing companies must now to a large extent train their own men. These men must have a thorough acquaintance with the organization, must know the apparatus manufactured by it, and must be more or less familiar with the general business conditions and with the individuals handling that business. In a large electrical manufacturing company the ability to handle business in almost any department is to some degree dependent upon the familiarity of the individual with the apparatus concerned, as commercial, legal, and engineering questions are almost always involved together.

A manufacturing company naturally desires a considerable variety of men. There is a large amount of routine business to be transacted, and there is also a large amount of work calling for originality, initiative, and invention, which demands a different type. Men may remain in the shop organization, enter the general commercial department, enter the drafting room or engineering force, work out into the district offices in their engineering or commercial lines, may go with operating concerns to take charge of power plants and transmission systems, or they may branch out into the very wide variety of allied industries which use electrical apparatus and where trained electrical men are required. A considerable number find a useful field in consulting engineering, and a few get into positions where technical engineering ability is utilized in financial lines.

Some manufacturer has said that he could lose his whole factory equipment and still win out if allowed to keep his organization intact. Certainly organization is one of the most important factors in present industrial conditions. An organization means an aggregation of individuals each of whom is performing some more or less specialized function, but all working harmoniously together to a common end. Many men never learn that they are part of an organization, and persist in working as individuals and therefore lose much of their value to a large concern. To get the advantage of a large organization everybody's mind must be used for the whole, and the old military system of passing down all the orders from the top has largely disappeared. Coöperation is the watchword of modern industrial development. Conferences have become a standard way of arriving at decisions, but executive work must, of course, be single-headed. Concerns which make use of the idea of conferences and of using the minds of all of their members, while they may be a little slow in action, will always win in the end. The best organizations allow a free development of individuals, while restricting them to harmonious action. Initiative must be rewarded, suggestions freely accepted, and a healthful rivalry carefully watched and, if necessary, restricted. An individual entering a large concern becomes at once a member of an organization and must work as such. The entire line of thought and action is very different from a condition where he performs all functions himself. The ability to work as part of an organization can be largely acquired, and should be learned in a college course. It is usually one of the things which a man has to learn when he first gets out of college, and is sometimes rather a difficult lesson. Great importance is placed by manufacturing organizations also on personal habits, characteristics, etc., as well as mere technical knowledge.

The condition of a man after graduation depends to a considerable extent on the individual and somewhat on the college from which he comes. The recent graduate is necessarily somewhat theoretical in his point of view, and, while having a good foundation, has not the practical experience or the acquaintance with actual conditions which makes him of immediate value. There is a tendency at present to connect educational institutions with manufacturing establishments so closely that there shall be no sharp line of transition from one to the other. This looks somewhat ideal, but undoubtedly is a desirable tendency. A great deal in the present system is to be commended, and splendid men are being turned out. They are all willing to start in at the bottom, but very few are willing to stay there long. The ability to succeed in an industrial organization depends on a great many other things than mere technical knowledge, and the incidental developments at college bring out many faculties which are useful in later life. The participation in college athletics, debating societies, class functions, fraternities, publications, etc., develops the individual and assists him to follow such work after graduation. Cramming for examinations has even been commended on the score that this is what one has to do continually afterwards. Among the most importtant things which a man learns to do at college, especially in athletic contests, is to work with others; to do team work and not act as an individual, because a large part of the effectiveness of an organization depends on just such work. A college man naturally becomes something of an organizer, promoter, manager, and contestant, and gets a start in taking a broad view of conditions. It is dependent upon himself to develop this afterwards.

One of the most promising signs of the times is the close study and coöperation between manufacturers and colleges. College students frequently work in the shops during vacations, as do also college professors. In some colleges it is the intention to have the professors engage for a year or so in active practice, and then return to teaching for a few years. The whole trend is along a line which brings the college man in close touch with actual conditions. Much that the colleges are doing is excellent, and much can be said in favor of the ideas now being given consideration for future modifications. A few suggestions only are offered here.

The college graduate during his first year or two after graduation, is placed under new conditions, and requires some time to find himself. It has been suggested that he keep some relationship with his college during this time and that some systematic study in connection with this work be followed. Another suggestion is that college work should be from the beginning associated directly with the idea of costs. No real engineering is ever dissociated from this feature. It usually takes a college man some time to learn that the best engineering is that which will serve the purpose, and cost the least. At least one college runs its shop in this way, and to instill this point of view into men while getting their education would be of much use afterwards. It is very easy to say what should be added to or taken from a college course, and it is only too easy for a man to make suggestions in this line, as is evidenced by the amount of material produced in the way of articles and discussions. Many men after graduation find a use for commercial law, for accounting, for a certain knowledge of business methods, and financial factors. It is suggested that some attention be paid to these in connection with engineering work. Professional men are very largely working on salaries, and a salaried position is always more or less of an insurance against the acquisition of wealth, so that for professional men no subject is of greater importance than the study of investments, and from a personal point of view this cannot start too soon.

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# THE RELATION OF THE MANUFACTURING COMPANY TO THE TECHNICAL GRADUATE

BY B. A. BEHREND

Even though in times of business depression it may seem to us as if there were more applicants than positions, yet no thoughtful man denies that, while the number of positions in such times may have greatly decreased, the importance of filling them by thoroughly capable and competent people has correspondingly increased. For example, a position which, in times of exceptional prosperity may be filled fairly well by an average man, will be sorely in need of a man of exceptional ability when business prosperity is on the wane. If there is any one fact more patent than another it is the fact that there is always room at the top of the ladder for men of integrity, of moral courage, and of intellect. There are plenty of men who possess any one of these qualities; there are few who possess all three, and these the manufacturing companies, or the world at large, most require. In their anxiety to secure the raw recruits for officers thus endowed, the manufacturers turn of necessity to the universities and their graduates.

It must be granted that the colleges possess an almost unlimited potentiality for improving the human material turned over to them to shape and polish, and, it seems to me, considering the results obtained, they are doing very well in this shaping and polishing process. But they are not always supported in the right direction by the manufacturing companies. To allude to one instance only, I refer to the manner in which the manufacturing company seeks the young graduate, instead of letting him do the seeking. He thus gains, at the outset, an exaggerated idea of his importance, and an independence which is not conducive to the development of those qualities which make thoughtful and painstaking men. Our graduates are chiefly deficient in these qualities, and this is due, not so much to an innate deficiency in this direction, as to the fact that the incipient faculty has never been properly awakened and cultivated. There is abroad amongst our colleges and their graduates a most ominous disdain for painstaking accuracy and devotion to laborious detail, so essential to all really great work in engineering. The wish to take someone-else's thought and work and make it a commercial success, which is so prominent a feature of our business life, is easily explainable, though not so easily excusable. Men of ability realize that the same effort turned into the channels of commercial work will be productive of better returns than they would obtain by painstaking working out, for instance, the design and construction of electrical machines. In this case, even though their work may have met with eminent commercial success, our business methods are not much concerned with a debt of gratitude or obligation to the men that did the building up. Here lies a menace to the stability and continued prosperity of our manufacturing industries which must, in time, be remedied, lest it produce a far-reaching result in discouraging graduates of our colleges from the pursuit of new and important creative engineering work, with the result that we will have to draw on other countries for a supply of well-trained engineering brains.

The managers of our manufacturing plants can do as much toward the development of right views and proper education, as can the teachers and organizers of the colleges. The former need to study more sympathetically the condition of the latter, and *vice versa*. There are very poor pretenses of both managers and teachers in this world, and it is obvious that " the highest gifts are not always brought to the highest place." Education is a very good thing, but it cannot give the qualities which it should develop. Those who, like the writer, have been instrumental in the building up of large manufacturing organizations, recognize that the absence of moral qualities frequently mars a successful career, as frequently, perhaps, as the absence of purely intellectual qualities. Success often accompanies the work of men possessing ability, untempered by scrupulous restraint. Examples of this kind, so plentiful, have left a detrimental impression on the minds of aspiring young men. The thoughtful words of Mr. James Bryce, that this country " . . .

has the glorious privilege of youth, the privilege of committing errors without suffering from their consequences", remind us that many of our faults are not visited upon us with the unerring justice they deserve, because of the actual and potential wealth of this country in its present state of youthful and vigorous development. But let us not be deceived permanently into believing that, with our population increasing in geometric progression and thickening in our cities and manufacturing centers, many of the crude and lavish methods, despite which our industry is the most flourishing in the world, can be permanently retained without doing infinite harm. Space does not permit me to do more than to indicate the line of thought I wish to suggest. We need both character and intellect in our graduates, which should be cultivated by close coöperation between the manufacturing companies and the colleges, but for creating which no panacea has as yet been devised.

## DISCUSSION ON "A NEW METHOD OF TRAINING ENGINEERS," AND "THE RELATION OF THE MANUFACTURING COMPANY TO THE TECHNICAL GRADUATE." ATLANTIC CITY, N. J., JULY 2, 1908.

**B. A. Behrend:** Permit me to discuss the paper by Mr. Alexander, suggesting a new method for training engineers by alternating shop work with college work. Let us see how difficult it would be to have such courses at institutions situated far away from manufacturing centers like Cornell, Leland Stanford, University of Wisconsin, or Pennsylvania State College. How could the students in these universities attend the lectures for one week and go into the shops for the next week, or for one month and go into the shop for the next month? There are no shops or manufacturing plants near enough in which the students could pursue practical work, and thus the proposed "Coöperative System" is altogether impossible in a large number of our universities. Furthermore, be it remembered that there are only half a dozen manufacturing companies in this country in which the variety of work is great enough to give the student an idea of the engineering and manufacturing problems arising in the building of electric motors and generators, incandescent lamps, steam turbines, gas engines, and other machinery. In small shops, confined to the making of specialties, the student is not apt to learn more than the mere handicraft. Trades have ceased to be crafts, as discoveries and inventions are constantly changing the industries so that apprenticeship to a certain trade is gradually losing its importance. Knowledge of fundamental principles alone can successfully take the place of the old apprenticeship course. The coöperative system of education, as I interpret it, in accordance with Mr. Alexander's suggestions, would effectively prevent the student from concentrating his mind on any subject whatsoever. I have never seen a complex question which could be completely solved or brought to a conclusion within a week's time or a month's time. Take a boy off the work and put him into the shop, and what is to become of the labor he has expended in familiarizing himself with the problem? Vice versa, put a boy in a machine shop or foundry and teach him for a week the kinks of the trade, and then send him back to school for another week or a month: what is to become of the labor which he has expended in familiarizing himself with his shop work? In either case the work and time spent in preparation will be entirely wasted. It is like starting and stopping, accelerating and retarding the boy's mind continually instead of allowing him to obtain a given velocity and momentum.

The term "engineer" is made to cover so wide a field that it is necessary to define it to prevent confusion. The engineer who is bred at a university should have full command of theoretical knowledge. He should learn at the university principally what he cannot learn in after life. After graduation he may obtain some practical shop experience and, if he happens to be an electrical engineer, he may pass through the two years students' course of any one of the large manufacturing companies. With some shop work during his vacations, and probably a year's shop work after graduation from high school, his training should not be held responsible if he does not become a successful engineer.

There is, however, a much wider field for men in possession of some moderate theoretical training and of good practical knowledge. A large number of electrical and mechanical engineers are needed in the manufacturing industries as foremen, superintendents, and master mechanics, to whom a long scientific training would be of little or no advantage. For the training of such men there are provided abroad technical schools, professional schools, or technical middle schools as they are called, in which such a coöperative course might be feasible. You need to give these men chiefly a practical education and enough light, as far as theory is concerned, to obtain an insight into the principles and the working of the machinery which they handle and take care of.

If we set aside certain colleges of ours for the purpose of giving a good practical education to a class of men who are not likely to be concerned in later life with the difficult and complex questions of engineering, I can see no objection to adopting a coöperative course in these technical schools. When, however, we are told that this alternating course should be introduced into our universities, permit me to say with much emphasis that I think this is the most vicious educational innovation that has been proposed in recent years.

**J. P. Jackson:** I have heard many times the statement that the college graduate is not prepared for his place in the world when he leaves college. In reply to this criticism, I would like to say to the practising engineers, that if such is the case, they alone are responsible. The engineering college is their servant, and they can make it what they wish. It is their duty, as practising engineers, to take a positive and actual part in the college work.

Mr. Rushmore said that in teaching, we must consider the costs and economic questions. In our technical courses we have been weak in political science, in social and economic science, and in history. I consider that general history should deal with scientific development, as much as with political and economic movements, and I want to refer the weakness in this subject to your educational committee as one worthy of consideration. Along with suitable history, extending to the end of the course, should be studies in political science.

**Elihu Thomson** (by letter): Mr. Alexander has so fully described the proposed plan of coöperative education for the training of engineers that it is not necessary to refer to any of its details which would naturally be the subject of modification, according to the results of experience. The plan itself or some modification of it has seemed to me to present the possibility of results of such value that it is worthy of an earnest trial. Experience only can determine its true relation to other methods and courses of education. Involving as it does the feature of allowing the student to earn reasonable pay for his shop work, it would serve as a material assistance to those upon whom the expenses of the ordinary technical school would bear very heavily, or become a preventive of the attendance of those otherwise well fitted therefor. It would act to broaden opportunity, and this is of course very desirable in these days. Naturally such an education must be limited to those who manifest a capacity for it, and it would assist the student in an early determination of his fitness or natural aptitude for various kinds of work.

The earlier this discovery or determination is reached the better it will be, serving as a guide in future development. Naturally a combined course such as that outlined in Mr. Alexander's paper cannot be completed except by an extension of time of the school period. It is assumed, however, that upon the completion of the period of six years, the student will have the very real advantage of having had contact with actual practical work and its conditions instead of requiring much time to adapt himself to them. The attitude of the engineering or manufacturing company towards the plan will depend on possible benefits, such as securing for its force a selection of men well-trained practically and theoretically.

**Percy H. Thomas:** Broadly speaking, the theoretical training of an engineer, in my judgment, should come properly before his familiarity with commercial work. On the other hand, he cannot get the full benefit of his theoretical training without some knowledge of commercial conditions. Since the latter part of his theoretical training is the period in which a knowledge of practical work is of the greatest importance, it would seem that the gain which can be obtained by interlinking the school training with the practical work may be obtained by overlapping the last part of the school course with the beginning of the practical work. To carry this overlapping further at the present time would appear to me, however, to be a great risk.

I notice that Mr. Alexander suggested the cutting out of the shop work at the college. I do not believe that this would be wise. The character of the training from the college shop work should be a very different thing from the practical experience in the factory. There is much about the nature of materials and the characteristics of machine tools which is gotten very imperfectly, if at all, in the factory, and is gotten very quickly in the college workshop.

The distracting of attention from the theoretical groundwork of a man's education before its substantial completion, by awakening a keen interest in the commercial work, is a great danger. I do not believe that the man before graduation should be permitted to get deep enough into the commercial work of the manufacturing company really to feel its inspiration.

If there be any advantage to a poor student, by his being able to utilize his labor in the factory, this fact is to be considered, and commended; but personally I do not believe that this consideration is a controlling factor. The dropping of the work in the factory to return to the college is an incidental disadvantage to the man who wishes to get ahead, in that whatever connection he may have gained in a certain definite line of work is thereby broken.

**Morgan Brooks:** Mr. Alexander has taken up this question from the manufacturer's standpoint. I desire to say a few words from the point of view of the technical school. Many of the boys entering college directly from the high school are entirely too young to do satisfactory work in a manufacturing establishment. College training for the youth is not merely mechanical drawing or mathematics, but it is the developing of character. I assume that Mr. Alexander has in mind men of twenty-one or more who lack a college training. We sometimes get boys of sixteen who need college restraint and discipline as well as physical training before they are ready for heavy work.

The difficulty of arranging alternating periods for a group of students would be very great, unless every individual were required to take the same work. Election of subjects such as German, French, English, or history, and the selection of different technical subjects as well, would be impracticable. We would find only one or two students out of twenty who would wish to take certain courses, and it would not be feasible to assign separate instructors to each of these small classes. The student would be obliged to adopt a course selected by others, and thus lose one of the opportunities of a university—the selection of subjects according to his own taste or need. By making the period of alternation the half year or college semester this objection would be greatly reduced.

College training should not necessarily be expected to turn out a productive engineer upon graduation. At first, graduates are often at a disadvantage compared with regular apprentices, but the fact that they rapidly attain success is proof of the value of a technical training. The failure of some technically trained men ought not to create surprise. Training can only increase opportunity or accelerate progress; it cannot produce an engineer from nothing. The men who are successful without college training, and we have many such, would no doubt have gained success more quickly with it. They are the kind of men to make their mark in spite of the lack of technical education,

**Henry H. Norris:** Mr. Alexander outlines a plan for improving technical education which differs from the standard method in that practical and theoretical instruction are separated and alternated. While it possesses many obvious advantages, from the teacher's standpoint this coöperative plan appears to ignore certain difficulties with which the educator has to contend. Although the technical student is in many ways an ideal pupil, he has certain characteristics which must be kept in mind in devising plans for improving present methods, which are the result of evolution and which are, presumably, as satisfactory as can be expected under existing conditions. In technical education the teachers must work and plan for the average student. The brilliant student does not concern them particularly, nor does the very poor student; the former looks out for himself, and the latter is automatically taken care of by a natural process of elimination. The average student is the one whose characteristics must be kept in mind in discussing any particular plan.

In the first place, the average man prefers to work with his hands rather than with his head; for example, a student will usually take more interest and pleasure in building and testing a motor than he will in calculating accurately what the torque in that motor will be when the machine has certain physical characteristics. Again, students lose interest in theory when they become very much absorbed in practical work; that is, they seem to like the practice better than they do the theory. Therefore, in technical training there should be included just enough practice to produce facts to think with, and no more; just enough facts to furnish the material for organization.

A second and important feature is that there is always a loss of time in starting up after a change in mental occupation This is illustrated particularly in the case of vacations. There is a lag of a week or ten days after a vacation before the mental machinery gets into smooth working order. The student in taking up his work at the end of a vacation acts as if he had a large inductance, and toward the end of the term he acts as if he had a large capacity; he starts slowly, he stops quickly. During the past year at Sibley College, the problem of reducing the frequency of these oscillations or alternations of work has received careful attention. Many professors advocated terms of four months, without interruption, alternated with vacations of substantial length. The general faculty of the university rejected the plan because there was difficulty in arranging a schedule to meet the needs of all the colleges of the university, but Sibley College stood for a plan involving two complete cycles per year.

A third fact which has a bearing on the coöperative plan is that when an individual knows that a task is to be dropped, whether completed or not, at a certain time, he loses a sense o responsibility with reference to that task. This sense of responsibility is an important element in successful teaching and it should be retained to the maximum possible extent.

There has been some discussion as to the place of shop work in the college. In my opinion shop work should be kept in the college curriculum, because the shop is the laboratory for teaching the principles of manufacturing. The principles of manufacturing can be taught better in college, by competent persons, than in the manufacturing establishment itself.

Mr. Rushmore suggests another plan for improving technical education. This involves no radical departure from existing practice, but rather a more efficient use of the means already at command. In most of the colleges there exist arrangements whereby advanced degrees may be secured *in absentia*, by proper registration and examination. In many cases the present methods of administering and supervising this work need considerable improvement.

**Charles P. Steinmetz:** Speaking from the point of view of the college professor, I appreciate that there are many things which it would be very desirable and important to teach in college, such as factory management, shop work and languages. We could teach them if we had a college course of eight or ten years. The question is not what it would be desirable to teach in these four years, because we cannot possibly teach in four years everything that the electrical engineer should know.

It appears to me that the guiding principle, in regard to what should be taught and what should not be taught, is that the college should teach all that which the young man can never learn after leaving college, and drop all those things which the young man can learn after leaving college. The humanities, the scientific foundations of electrical engineering—such as mathematics, principles of mechanical and civil engineering, engineering mechanics, physics, chemistry—these cannot well be learned afterwards, but subjects like practical work, factory management, business administration, etc., while very essential and very important, can be learned afterwards, and usually better than in college.

Colleges have been criticised because the young men are not fit immediately to fill important industrial positions, but have to learn in practice what the college can not give them. Now from my other point of view, that of a user of young men, I do not consider this state of affairs a criticism of the college. On the contrary, if a college were to turn out young men who could immediately drop into positions in our industrial organizations, I would very strongly suspect that that college had wasted the young men's time by teaching them things which they could learn just as well, if not better, afterwards; and that, therefore, many things which they should know but can not learn afterwards had not been taught. I do not believe the college graduate should be expected to be ready to enter immediately into full engineering practice; I believe he should have all the requirements to develop in due time into a first-class engineer.

We must not forget, however, that the college is not the only educational institution. There are other important educational institutions for electrical engineers. There are trade schools and correspondence schools. They do work the importance of which many of you do not appreciate, work of the highest value, and I want to speak here for them and draw attention to them so that we may give them proper recognition.

**Dugald C. Jackson:** We must remember that the problem of education is physiological and psychological. Education is not one of the exact sciences. The American Institute of Electrical Engineers has had placed before it in more than one paper the very distinct difficulty which engineers find in applying mathematical equations to the phenomena of what we call the exact sciences, such as physics, and we may as well start upon the proposition that we have no basis upon which to lay even the foundation for an equation of education. We are consequently compelled to rely entirely on the experience of the past in drawing our conclusions in respect to education. This is a very unsatisfactory basis upon which to found an advance, but it is the best we have. In passing, I may say that it is as good a foundation as Watt had for his physical science at the time that he made the modern steam engine; it is as good a foundation as George Stephenson had for his physical science when he succeeded in demonstrating that steam locomotives could cope with horses and displace them for transportation; and it is as good a foundation as was possessed for their physical science by most of the great inventors who produced the fundamental processes of our present industries and brought us the kind of civilization we know today. We may therefore believe that there is no reason for pessimism because we do not yet possess a firmer foundation for our reasoning about the methods of education.

As far as engineers' education is concerned, I think we will agree that we are here looking at it as *professional* education. We will probably all of us agree that we want to see the greater engineering schools aim at producing men of tremendous worth who will go far as engineers. The lesser engineering schools, trades schools, and others, will take care of the lower grades in the engineering arts; but so far as the greater engineering schools are concerned, their educational efforts should rest on a foundation of fine, thoughtfully taught literature, history and the other subjects of " humanistic " interest, including the languages; but whatever these efforts are founded on, it is distinctly professional education that the engineering schools must carry on.

The history of engineering training has much in common with the experiences of other professional branches. The early engineers were trained by becoming articled apprentices to principals who were supposed to direct their reading in natural philosophy and the like, and at the same time give them opportunities for actual engineering work. The earlier engineering schools dealt with civil engineering. They afforded advantages over the older way because the students were required to study with greater fidelity, and practice of the old type of civil engineering could be actually mixed with the studies. The situation has been quite different with the provisions for mechanical-engineering and electrical-engineering students. School shops, however well operated, have never afforded an equivalent of the inspiration or the practice that may be derived from association with a large, diversified, and well-run manufacturing establishment. In the latter respect, the engineering schools now labor under the disabilities analogous to those pertaining to the law schools before the general study of cases and practice in the moot courts were introduced in association with the study of the philosophy of the law, and to those pertaining to the medical schools before the association with hospital and general practice was thoroughly worked out.

It seems to me that Mr. Alexander's proposition has a strong foundation of precedent resting on professional education in other branches, and that the plan is one to which it is desirable to give a full and complete trial; and it is to be hoped that arrangements can be made for such a trial to be given. I have had an opportunity to study carefully Mr. Alexander's particular proposition. I have become convinced that this plan properly utilized may do much for engineering education, as the analogous plan properly utilized has already done much for law and medical education. Such a plan would not convert the young men into engineers who would be prepared to do the work that can only be done by men of twenty-five years' professional experience, but it would afford the young men a scientific and humanistic training equal to that which they now get in the best engineering courses plus much more acquaintance with the qualities of men and affairs than they now get in two years of what are called "student apprentice courses" in the factories. In addition to all that, the young men who followed a well-administered plan of the type proposed by Mr. Alexander would have pursued their scientific and humanistic studies in the school with an appreciative understanding of the tremendous results that can be brought about through coöperative effort, and of the necessity of dependability and thoroughness in all important work, and also of the tremendous possibilities which exist for the use of the highest type of talent in the engineering industries. In these three important factors, which should lend an inspiration and a quickening of ambitions of the highest importance, our young men now graduating from engineering schools are commonly defective. It seems plain to me that the engineering schools must in some manner improve their processes if they are to make the men who will *go far* in the engineering industries of the future; and if they are to try an experiment, there is nothing which looks more likely to bring good results than this plan which is an analogue of the plan that has worked advantageously for the medical schools and the law schools.

I do not mean to suggest that it is necessary to have every engineering school close to a great manufacturing establishment in order that the improvements which are here in mind may be substantially brought about. An engineering school of fine grade close to a great manufacturing establishment which carries on a highly diversified business, and which is well organized, and which will deal with this sort of experiment in a sympathetic manner, will possess an advantage due to its position. But the schools that are isolated can work out their own shop and laboratory methods so as to bring very much of the same plan into effect; though it is my belief that no engineering school has yet approached the requirements, and also that an inspiration may be secured by the students' association with proper manufacturing establishments which cannot be obtained in the school shops.

**C. A. Adams:** Whatever prejudice or preconceived opinions one may have against this plan of coöperative engineering education, there are certain of the advantages claimed for it which are so desirable as to make one wish to see the experiment have a fair trial. Personally I am not yet ready to take a decided stand for or against the plan, although I incline to the opinion that its success will be much more limited than its promoters seem to anticipate.

The principal advantages which would accrue under the best conditions, in the order of their importance in my mind, are: first; social—the value of a fairly intimate association with large numbers of the so-called laboring class, the new point of view usually involved in such association; a consequent better preparation for the duties of citizenship; a better appreciation of the advantages of a college education, and more sympathy for those less fortunate: secondly; educational—the advantages under this head have been fully described by Mr. Alexander.

The principal disadvantages are: first, the numerous practical obstacles to the carrying out of any such plan, such as the difficulty in coördinating the college and shop work where there are several groups of men taking quite different college courses; the frequent change of residence; and the difficulty in finding suitable shops where the influences are such as to make possible the attainment of the advantages above described; secondly, the danger of over-emphasizing the commercial side of engineering. This I consider a very serious danger, although I realize that there are different opinions on this point.

A system adopted in Harvard University recently, follows pretty closely the suggestions made by Dr. Steinmetz. Each undergraduate registers in Harvard College, where his studies are almost wholly elective. If his preference be engineering, he is advised to lay a good broad foundation in science, mathematics and languages, and, where time permits, to take some general or cultural courses. Meantime he associates more or less with men studying in widely different fields and has every opportunity to determine whether or not his taste and ability lie in the direction of engineering, and if not, in what direction they do lie. After the completion of a certain number of courses, he receives the appropriate degree, A.B. or S.B. If the student still prefers engineering after graduation, he registers in the Graduate School of Applied Science where he completes his engineering studies in two or three years more, and receives the degree of master in electrical engineering or in the appropriate field. This school is thus a professional school similar to the law and medical schools. Its advantages over the old arrangement are: first, it insures a more mature choice of profession and eliminates many students wholly unfitted for engineering, but started in that direction by some one of the numerous chance elements; secondly, it encourages a more substantial foundation and a broader education: thirdly, it does not force each man through the same machine, but adapts the work to the wants of the individual. In short, it makes for a higher efficiency of education.

**A. F. Ganz:** If I correctly understand Mr. Alexander's coöperative plan, it is based on the principle that the student should learn some theory, then go into the factory and get some practice on that theory; on that basis he has planned a six year course, which is equivalent substantially to three years of factory work and three years of college work. Now all of us who have been teaching in technical schools know that our present four-year' course is already crowded, and this proposition would cut down our time for teaching theory from four years to three years. Mr. Alexander suggests that the time can be gained by cutting out shop work, a large part of laboratory work, and mechanical drawing. I do not believe that is possible. If the shop work, the laboratory work, and the mechanical-drawing work have been properly planned, —that is to give the student that information which he cannot get in practice—then I do not believe that the practical work in the factory can be made to take the place of the laboratory work and of the mechanical drawing. I believe that it is the main function of the laboratory to run parallel with the theoretical course in the class-room, and to give to the student practice, with his hands, of the theory which he has learned in the classroom.

I thoroughly believe in allowing the graduate from the technical school go into the shop and get practical experience; but three years of practical work mixed in with three years of theory is too large a proportion of practice. When we look through the usual curricula of our technical courses, we find in the first two years, largely, subjects like mathematics, physics, chemistry, and general cultural subjects. Now, surely, in the factory the student will get no practical experience which will help him in an understanding of any of these fundamental and very important subjects. It is only in the third year that we can begin to teach engineering work, and the best plan, it seems to me, for carrying out the suggestion of coöperative education, would be to let the student go out for one year during his college course, preferably between the third and fourth years, after he has had a good deal of theory. He should go into a large shop where a great variety of work is done, and not into a small shop, where only special machinery is built.

In regard to breaking into the theoretical work, several years ago Stevens Institute adopted a plan of having three terms, a first term of 14 weeks, then an intermediate term of 4 weeks, and then a third term of another 14 weeks. The object of the intermediate term was to give the student 4 weeks for solid practical work in laboratories, drawing room and shop. We have now abandoned this scheme for a number of reasons, one reason being that at the beginning of the third term we found that it took the student some time to get back to the theoretical work. I do not believe that this plan works nearly so well as the plan to make the theoretical work continuous and to put the practical work at the end; that is, in a summer term.

**Chas. F. Scott:** A good deal of our discussion of engineering education is, if we analyze it, really the consideration of a human slide-rule. We want a man to be capable of doing certain things. We consider, in a mechanical sort of way, that he should know how to do this, that, and the other thing, and we are apt to try to crowd into a curriculum more subjects than it is possible for the college course to cover adequately. But in the engineer it is not so much mere ability in mechanical calculations or manipulations that we care for, but some higher quality—a higher quality of mind, life in some higher terms, if the purpose of education is to translate life into its highest terms, the development of its consciousness, of its soul qualities, thinking and feeling, of its forces to direct conduct and control purpose. These indicate some of the things that we want in engineers as men; we want to develop men, and when we have the man it is a lesser question whether he is an engineer, or a doctor, or something else. We want the foundation for this larger usefulness; we want a man to get his life into the largest terms, by the development of himself as a man.

In engineering education, then, we want a general purpose and policy towards which to aim. The method of carrying it out is almost of secondary consequence. It cannot be the same method everywhere, and different methods, particularly in this period of evolution, are desirable. The new plan which is about to be carried out in Boston has its pros and cons. I think it is a most fortunate thing that an experiment of that kind, if we so choose to call it, can be tried. We need variety in methods as a means of gaining experience and as a tonic in our work. There is certainly one thing which will be gained by a method of that kind; it will give to the man the facility to adapt himself to conditions, to bring his theoretical and practical training to one side or the other, thus maintaining a just balance.

We separate too much the theoretical and the practical: they must go together hand in hand. I have in mind now some investigations Mr. Thomas carried on a few years ago, and it seemed to me his method was ideal. He would take his problem and study it, and work it out in mathematics, in $x$, $y$, and $z$, and come to a certain conclusion, and then undertake his test. He would get experimental results which gave him constants for his formula work, or which indicated some factor which had been omitted and which needed now to be included. He would then go back to the study of his formula, and integrate his new experience, which would give him a new hold when he came back to experiment.

One of the purposes in the apprentice courses as now conducted is that they change the point of view of the student. He has been in college, where he has been passive; he has been directed. Then when he goes out to the manufacturing company he feels that this is now his post-graduate course, and he waits for experience to be pushed into him, but he does not find the foreman running around with bits of experience to add to his information. He is at a loss for a time, and then finds he has to shift for himself; has to change from the passive to the active; for it is sink or swim. That is one of the best experiences of this apprenticeship course. Now, if in this Boston combination the school idea predominates, and the student is simply led around through the factory, and feels that everything there is simply for his benefit, and he fails to develop self-reliance, then something is going to be lost.

**Gano Dunn:** I have observed that the most effective graduate is the man who, somewhere in his college course has had a taste of practical experience, the man who has had at some time actually to earn his living. Contrary to the opinion of Mr. Alexander and of Professor D. C. Jackson, I think that the desirable contact with practical work cannot take the intimate form that they recommend. A college course should teach men what they cannot learn in after life. The very specialization of a college course contributes to learning some things more thoroughly than they can ever be learned when alternated with business activities. The subjects at college mutually support and illuminate one another. Intermittent college and practical work would, I fear, destroy this benefit.

The reason college graduates who have had practical experience are usually better than others, is not principally because of the things they have learned about technical subjects during the course of that experience, but because of what they have learned about life in general and the problems of discipline.

The *average* college student is not a man of much directive force. His tastes are not strong, and he is not very particular which way he goes. He needs polarization. If he can get it before he enters college or in the early part of his college career it will enormously increase the efficiency of his education. I attribute the greater effectiveness of the college graduate who has had experience to his early polarization in the field of life and his early submission to the discipline of the world.

From the manufacturer's point of view there are many obstacles to Mr. Alexander's scheme, even if there are none from the point of view of the educator. In surveying the field and taking note of the number and size of the electrical factories and the number and output of the electrical educational institutions, I think each manufacturer would be unable to take his quota of the electrical students. One very large manufacturing company might absorb all the students of one educational institution; a rough calculation indicates, however, that a proportional distribution of electrical students among electrical manufacturers would be more than the manufacturers could digest. The manufacturer holds on to even relatively low-grade employees, carrying them over dull times, remembering their loyalty and faithfulness in performing various operations. This asset, of greater value than most people realize, would be lost if workmen were changed once a week, once a month, or even once a quarter, whether these workmen were college students or not.

Without wishing to be taken too literally, it is a good thing for a student, somewhere in his college career, to " drill brass name-plates for six months " as in the case cited by Mr. Rushmore. It is a mental training. It corresponds to what a man gets in other countries in the army; and if while he is drilling brass name-plates the man is of the kind of selected material that Mr. Steinmetz would have the colleges accept, he will absorb, through having his eyes and ears open, a vast amount of knowledge about the organization of business, the democracy of relations between hands and foremen, the necessity of co-operation, and many other things that sooner or later he must surely learn.

I would add a word in most earnest support of the idea that we train only selected material at colleges. This is the true keynote to higher efficiency in education. It carries along with it, however, the obligation to employ only selected instructors. In many of our educational institutions we have as instructors men who, however learned, do not possess the art of imparting their knowledge, who do not know how to make a lasting impression on the minds of their students, who do not appreciate what to emphasize and what to suppress; men who in the delivery of their lectures, for instance, do not have that touch of dramatic power that causes students in later life to look back to those lectures as the very foundations of their technical training. A high standard for instructor material must go hand in hand with a high standard for student material.

**M. W. Alexander** (by letter): The discussion of my paper indicates an impression on the part of some that my plan intends to supplant existing college engineering courses. A careful reading of the paper, however, would show that this is not the case. The underlying thought of the proposed plan is to provide an education especially adapted to the needs of prospective engineers who are to specialize in life along administrative and executive rather than purely engineering lines. These engineers must have an adequate practical as well as a thorough theoretical knowledge of engineering; and the best method to accomplish this, I believe, lies in an arrangement whereby the engineering education at college is aided and supplemented by a familiarity with the industrial methods of progressive manufacturing enterprises, which may best be gained through simultaneous participation in the practical work. The plan, moreover, aims to enlarge the college sphere through a course which, for reasons already outlined, would attract to it capable young men, who, through one cause or another, do not or cannot avail themselves of a college education under present conditions. Obviously, the proposed arrangement, if carried into effect, will in time react upon present engineering education by suggesting changes which will bring the regular engineering courses more fully into synchronism with the demands of modern industrial life.

Mr. Behrend agrees with me regarding the general proposition when he says that "a large number of electrical and mechanical engineers are needed in the manufacturing industries as foremen, superintendents, and master mechanics"; he does not, however, fully appreciate the value of a broad education for these men who, after all, occupy positions as foremen, master mechanics, and superintendents only as stepping stones to something higher. Inasmuch as they are to become eventually leaders of men and managers of enterprises, they should receive an adequate cultural development in addition to their scientific and practical training. Again Mr. Behrend is pleading for my proposition—although unintentionally perhaps—when he claims that the proposed plan is "like starting and stopping, accelerating and retarding the boy's mind continually instead of allowing him to obtain a given velocity and momentum." That is the very thing I am aiming at, namely, to make and keep the young man mentally so alert that he will be able to adjust himself quickly to varying conditions as they arise; he should not need a headway, so to speak, in order to be effective. The mind of the future manager must be trained to work like a polyphase motor, starting under load and quickly acquiring full speed, and not like the ordinary single-phase motor which must run under full speed before it can carry load.

Professor Norris falls into a similar error when he criticises the proposed plan on the score that there is loss of time in starting up after a change in work. It is one of the very objects of the plan to minimize this loss by offering frequent opportunities for practice in changing quickly from one line of activity to another; and this inability to make quick adjustments is a weakness which manufacturers see in recent college graduates. A manager has to change his work many times a day; one hour he is occupied with engineering problems, another hour with financial questions and perhaps the next hour with matters pertaining to the labor problem or the economics of production. Certainly, we should aim to train for such managerial capacity those students who will take up administrative work. This change from one class of work to another may of course be carried too far. It is for this reason that I do not advocate weekly changes such as are provided under the coöperative plan at the University of Cincinnati. I am advocating alternative periods of from six to ten weeks' duration, fully ample for the concentration of thought and work to which Mr. Behrend properly refers. The courses of study in technical colleges will bear me out in this respect, for many of their subjects are completely covered during a similar period of time.

Again, I note with pleasure Mr. Behrend's support of my contention that a correlated practical and theoretical engineering education during the so-called college career will prove very beneficial for engineers who wish to engage in manufacturing business or to become executive officers of industrial establishments and public service corporations, for he says: "If we set aside certain colleges of ours for the purpose of giving a practical education to the class of men who are not likely to be concerned in later life with the difficult and complex questions of engineering, I can see no objection to adopting a coöperative course in these technical schools."

Assuming all the time that we are dealing with recognized engineering colleges which confer the usual degrees upon their graduates, it must be admitted that whether such courses are to be given in separate colleges or side by side with regular courses in the same college is, after all, a matter of detail. Local conditions will have to be taken into account, and it is by no means necessary to have these coöperative courses introduced in all engineering colleges. Naturally they would be established, in such colleges as are located near the large manufacturing industries, and they could prove their value in these particular instances, even though other colleges may not be able to offer the same opportunity. This argument against the proposed plan, put forth by Mr. Behrend, would hold just as good in advising Harvard University not to start its graduate school of business and commerce because other colleges are not in a position to do the same. Furthermore, inasmuch as I am advocating alternating periods of from six to ten weeks, and not of one week's duration, as Mr. Behrend erroneously seems to have in mind, it would be feasible for colleges and manufacturing companies to establish a coöperative course even though they should be separated by a distance of fifty or one hundred miles.

The coöperative course can only be open to a comparatively few, at the most, taking the factory side of the question into account; and it is therefore intended for those especially fitted for the work for which the course aims to train. While I, therefore, fully agree with Professor Norris that elementary education must be laid out for the average boy, I differ from him with regard to higher education in believing that the latter and especially the one of a technological character should differentiate and concern itself with the various capacities of the students so as to allow each, within reasonable limits, a full and free development. A young man should not go into an engineering college unless he is well fitted for an engineering career. Dr. Steinmetz is right in advocating measures by which the engineering college will eliminate the mediocre and develop only the well-qualified student. The latter should be taught the humanities as well as the sciences, and I am ready to go with Professor Norris as far in this respect as he wishes, for I plead for a broad educational training at all engineering colleges, so that the man as well as the engineer will be developed. Professor Norris' fear that students may lose the sense of responsibility for a task when they know that the task is to be dropped at a certain time whether completed or not, would disappear under proper training. To me this danger appeals with much less force than that concerning the lack of serious responsibility of our present college students, who, for four years, enjoy a delightful college freedom without any restraining influence such as intermittent discipline of practical life would bring. I should not want to deprive young men of this college freedom with all its great value, but I should wish to give it greater significance by giving it a background such as the factory discipline would furnish. The ideal of the college linked to the real of the factory is bound to be wholesome in its effect upon the character and stamina of the young men, who, under such conditions, will be developed, rather than injured by the awakening of a keen interest in commercial work, such as Mr. Thomas seems to fear. Experience, furthermore, refutes his contention, for those who during vacations engage in some gainful occupation, even though not at all related to the science of engineering, usually turn out to be good engineers. These students feel the inspiration of practical work, and through it, see clearer the value of a theoretical education.

The statement of Professor Brooks that high school graduates as a rule are entirely too young to do satisfactory work in a manufacturing establishment is surprising to me; if it were true it would be a serious indictment of our trade apprenticeship systems, under which grammar school graduates are required to do commercial work in factories, which they have been entirely able to perform without any inujry to their physical development. It goes without saying, of course, that the work in the factory must be suited to the physical maturity of the young man just as much as the theoretical work in college must be suited to his mental maturity. It must also be borne in mind that thousands of young men with a complete or partial high school education enter our factories and workshops and grow up into healthy and efficient men. Would not a periodical rest from the physical work with a corresponding period of mental activity develop these young men better physically as well as mentally? The elective system under the proposed plan would have to be practically eliminated, as Professor Brooks points out, but this is no objection to the plan. The elective system, however, even though our foremost educational thinker, President Eliot, fathers and favors it, is by no means regarded as the only method of securing an effective college training. The coöperative engineering course, aiming to train young men for a definite career, is an application of the elective system in the broadest sense of the term, for the student elects specific subjects which he must pursue in order to complete the requirements for a degree. The makers of such a course must lay it out on the broad basis of cultural as well as scientific instruction.

Some of the speakers have questioned the advisability of cutting the shop work out of the college curriculum. I think, we will all agree that so far as the term "shop work" at college refers to the teaching of the mechanical principles involved in machine work, the college should still attend to this part of education. The familiarity with machine processes, however, inasmuch as it is based on a more or less extended practice, could be left to the factory under the proposed plan, where it can be taught more effectively, inasmuch as it is taught by practical men and under real industrial conditions. In the proposed plan provision is made for the college to go much further in the educational phase of shop work by giving a more thorough and extended course in shapes of tools, cutting speeds and feeds, and similar important questions, than is done at the present time. Whether the college professor gives a course in these latter subjects at college or at the factory, or whether a practical man is selected as special instructor in these subjects, is, after all, only a detail in the whole plan. Similar arguments would apply to the part which the college and the manufacturing company ought to play in the teaching of mechanical drawing.

Considering the whole matter in this light, and studying carefully a detailed course of both the theoretical and practical studies under the proposed plan, Professor Ganz's criticism that a four-years' theoretical training is to be crowded into a three-years' period falls to the ground; for it will be seen that under the proposed plan as many, and even more weeks, are devoted to the college studies than are provided for at present in most leading technological colleges for the same subjects. As a matter of fact, the concrete plan which I have worked out provides for one hundred and thirty-two weeks at college, one hundred and forty-one weeks at the factory and thirty-five weeks for vacation, or a total of three hundred and eight weeks for the period beginning with the middle of July after high school graduation, and ending with the middle of June six years later. The particular college which I have in mind, devotes only one hundred and twenty weeks to corresponding studies during a four-years course. The extra time in the proposed plan is gained by a trial period of two months of practical work previous to the college work, and by a shortening of the present, I believe all-too-long summer vacation periods from sixteen to five weeks each. Furthermore, I firmly believe that coördinate theoretical and practical work as proposed will make it possible to cover more ground at college in a given time than can be done under the present system. A knowledge of practical work will materially help the student in a quick understanding of most of the engineering subjects taught at college.

In closing, I wish to emphasize again, that the proposed plan aims to train high grade manufacturing and executive engineers who may receive their college degree on the basis of a thorough engineering education, and besides have obtained an adequate practical training with special reference to their future usefulness.

Application of any theory, after all, will prove whether or not the theory is correct. Thus a trial of the plan which I have proposed will prove if it is efficacious; and I am glad to find so many members of the American Institute of Electrical Engineers ready to see a sufficient value in the proposed coöperative course to hope for a fair trial where conditions permit.

*A paper presented at the 230th meeting of the American Institute of Electrical Engineers, New York, October 9, 1908.*

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# HIGH-POTENTIAL UNDERGROUND TRANSMISSION

BY P. JUNKERSFELD AND E. O. SCHWEITZER

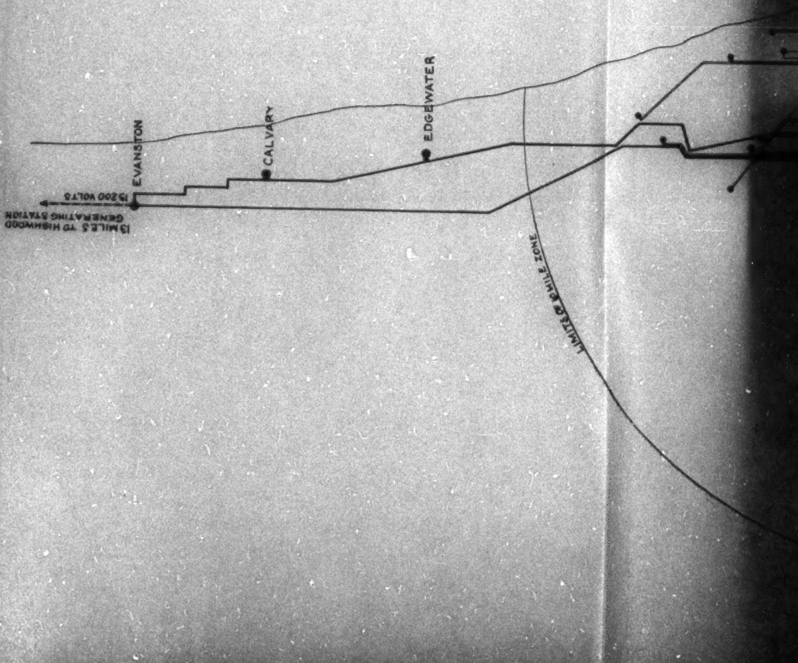
Among the many electrical developments of the day the most striking one, the most far reaching in its direct and indirect results, is the successful transmission of energy at greatly increased pressures. From present indications systems operating at potentials of 100,000 volts and over will not be uncommon in a few years, and none dare prophesy what further increase the future has in store. What this means to many communities from an economic and sociologic standpoint can readily be appreciated. Cheap power will enable present industrial communities to improve and new ones to build up in pleasant localities many miles from its source, whether coal or waterfall, and cheap traction will quickly carry their wares to market.

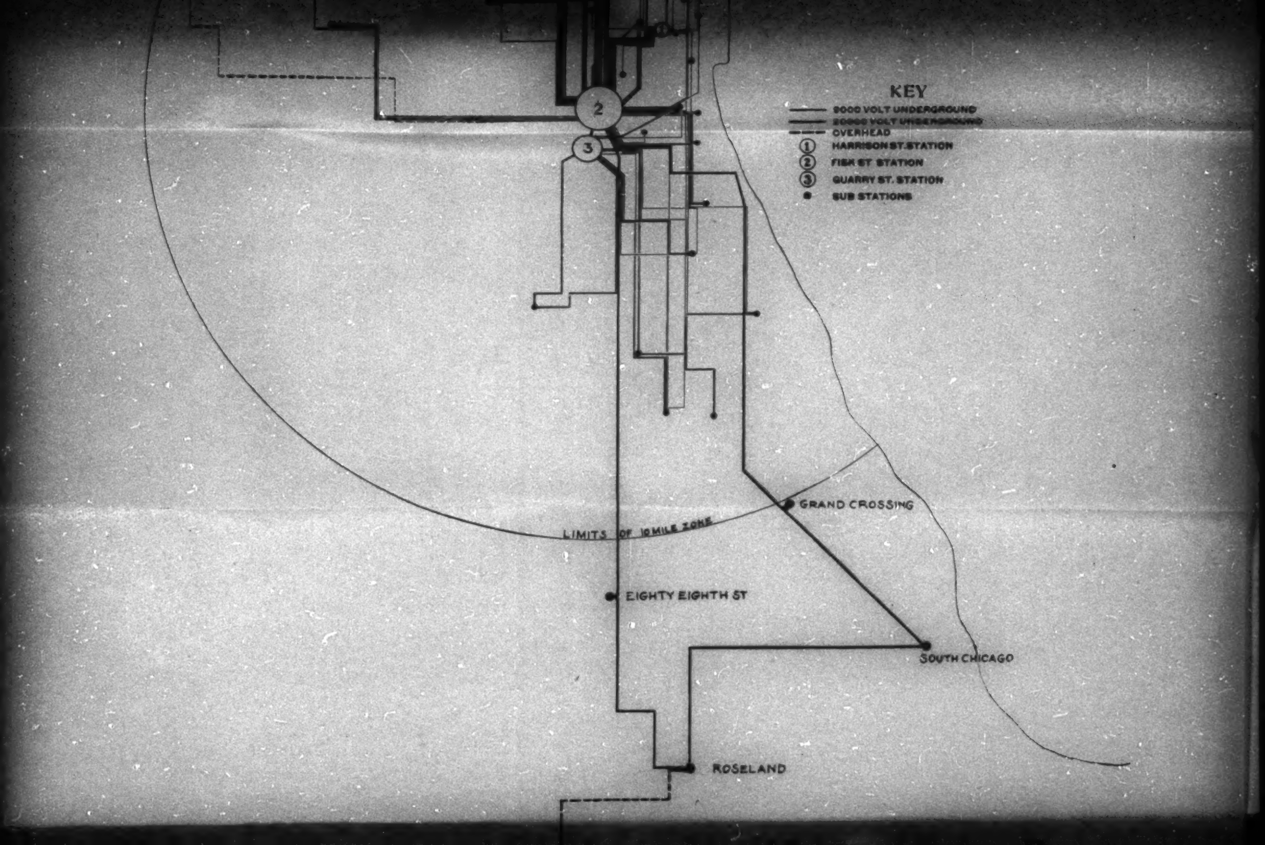
Within the confines of the largest cities the conditions are sometimes such that it is not advisable to carry these high potentials overhead. In such cases it may be necessary to place the conductors underground. The limitations of insulation and size have kept the transmission voltage for underground cables at about one-third that of overhead transmission, and while there has been a considerable advance in the art the approximate ratio of 1 to 3 seems to be still maintained. However, in large systems of underground transmission, insulation and size are not the only cable limitations. The line constants may become such that the cable is frequently subjected to dangerously high potentials. It therefore becomes advisable carefully to study the system so as intelligently to provide conditions for reliable service.

This brings us to the subject of our paper in which we shall discuss high-potential underground transmission, with a view of pointing out some lessons taught by experience and tests and of suggesting further investigation and discussion. It is not the intention to discuss cable manufacture or in any detail the installation or protection of underground cables, as these matters have already received careful and thorough attention in other Institute papers. Nor is this paper in any wise to be an argument for underground transmission as against overhead transmission. Conditions are frequently such that overhead transmission is the only practicable method. The increasing use of very high potentials is tending to raise the boundary between high and low tension, but at the present time the dividing line is still generally accepted as 5000 volts.

*Typical large cable system.* This paper will, therefore, not deal with experience at pressures lower than 5000 volts. A typical system using high-potential underground transmission extensively is that of the Commonwealth Edison Company of Chicago and its experience will be cited principally. The system is fairly well known, having been described in more or less detail in Institute papers and discussions and in the electrical press. Suffice it to say that at present (September, 1908) the system consists of two generating stations (a third is in process of erection) with a maximum capacity of about 18,000 kw. and 100,000 kw. respectively, sixty-six 9000-volt, three-phase, transmission lines aggregating 272 miles, supplying forty-four sub-stations containing synchronous converting equipment almost exclusively. Three additional sub-stations and 68 miles of additional 9000-volt cable are now under construction.

There is also a 20,000-volt line eleven miles long connected to the 9000-volt system through step-up transformers, and feeding railway and frequency changer sub-stations located in an outer or suburban zone. Forty-four miles of additional 20,000-volt underground lines are under construction, which will bring the total up to fifty-five miles. The entire cable system is shown in Fig. 1. This 20,000-volt system will be permanently supplied from 5000 kw., three-phase, step-up transformers connected delta to star with the neutral grounded. The standard size of 20,000-volt cable is 00, and of 9000-volt cable 0000 and 250,000 cir. mils. The 340 miles of 9000-volt cables supplying the densely populated inner zone form a so-called " radial system ", while the 55 miles of 20,000-volt cable when completed will form two so-called " ring systems ", one supplying the more sparsely settled outer zone northward and the other southward,


13 MILES TO HIGHWOOD GENERATING STATION
15200 VOLTS
EVANSTON
CALVARY
EDGEWATER
LIMITS OF 6 MILE ZONE


KEY
9000 VOLT UNDERGROUND
20000 VOLT UNDERGROUND
OVERHEAD
① HARRISON ST. STATION
② FISK ST STATION
③ QUARRY ST. STATION
● SUB STATIONS
2
3
GRAND CROSSING
LIMITS OF 10 MILE ZONE
EIGHTY EIGHTH ST
SOUTH CHICAGO
ROSELAND

The radial and ring systems are shown diagrammatically in Fig. 2. The principal station (Fisk St.) is equipped with steam turbines exclusively, four with a maximum capacity of 7500 kw. each and six of 12,000 kw. each. The generators are all star-wound and the neutral is grounded.

In February 1902 the 25-cycle, three-phase system of about 17 miles of three-conductor cable and seven synchronous converter sub-stations was raised from 4500 to 9000 volts, the equipment and cable having been installed with this change in view. This transmission system was first put into service in August, 1897. The greater part of the cable at the time of the change to 9000 volts was 00, some 0 and about one-fifth of 0000 size. The insulation on the original 4500-volt cables consisted of 5/32 in. inner wall of paper around each conductor and an outer wall 3/32 in. thick surrounding all three. The thickness of the lead sheath was ⅛ in. In the 9000-volt cable the thickness of the paper insulation was finally standardized at 6/32 in. and 4/32 in. respectively. The increase per year in mileage of cables operating at 9000 and at 20,000 volts is shown in Fig. 3.

*Other early cable systems.* Some of the high-tension cable systems in operation or under construction in 1897, when the transmission system in Chicago was first put into service at a lower voltage, were the following: Brooklyn Edison Company, 6600 volts (1897); New York Edison Company, 6600 volts (1898); Niagara Falls Power Company in Buffalo, 11,000 volts at end of overhead line (1897); the Metropolitan Street Railway, New York, 6600 volts; Twin City Electric Company of Minneapolis, 12,000 volts (1898). Soon after came Manhattan Railway, New York, 11,000 volts; Providence. Rhode Island, 12,500 volts; Milwaukee, 13,200 volts; and St. Paul, 25,000 volts (1901). The cables of the St. Paul Gas Light Company were two in number and formed the receiving ends of two parallel 25,000-volt, three-phase, overhead transmission lines 30 miles long. Each cable was about three miles long; one had rubber insulation and the other paper. Cable manufacturers at that time generally offered to make cable to withstand 30,000 volts pressure for individual lines, but for a network about 15,000 volts was considered the safe limit. About a year later this limit had apparently advanced to about 22,000 volts.* The insulation used on these various cables might be of interest and is given in Table 1.

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* Fisher, A. I. E. E. Trans. 1903, page 440.

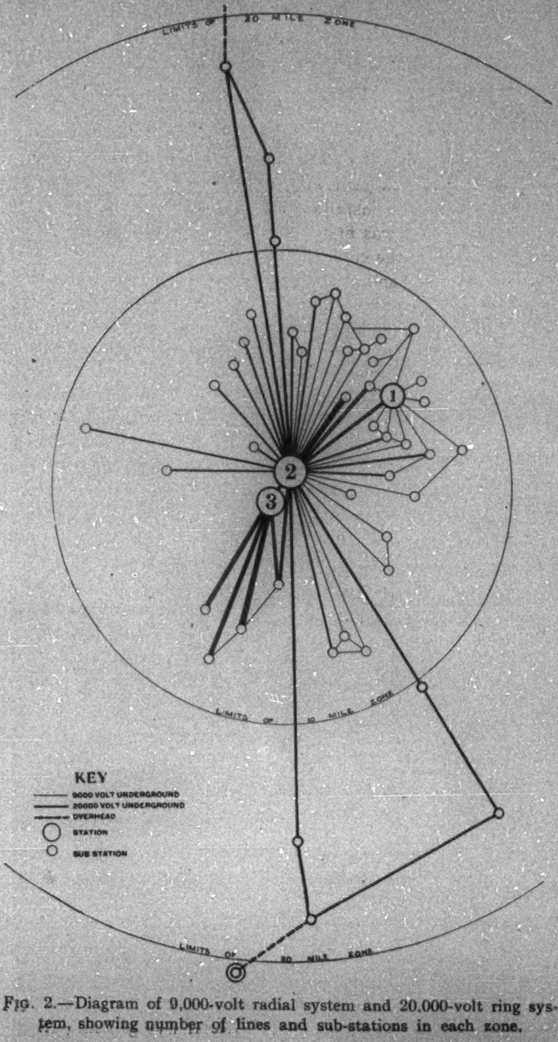
LIMITS OF 20 MILE ZONE
1
2
3
LIMITS OF 10 MILE ZONE
KEY
9000 VOLT UNDERGROUND
20000 VOLT UNDERGROUND
OVERHEAD
STATION
SUB STATION
LIMITS OF 20 MILE ZONE

FIG. 2.—Diagram of 9,000-volt radial system and 20,000-volt ring system, showing number of lines and sub-stations in each zone.

*Experience.* The early experience in Chicago and elsewhere showed the necessity for avoiding sharp bends and for using extreme care in making the splices. A small number of burn-outs occurred during the first year's operation at 9000 volts, and nearly all were due to sharp bends or to moisture at the joints. In order to determine how quickly moisture in a cable causes a breakdown, after it has entered through an opening in

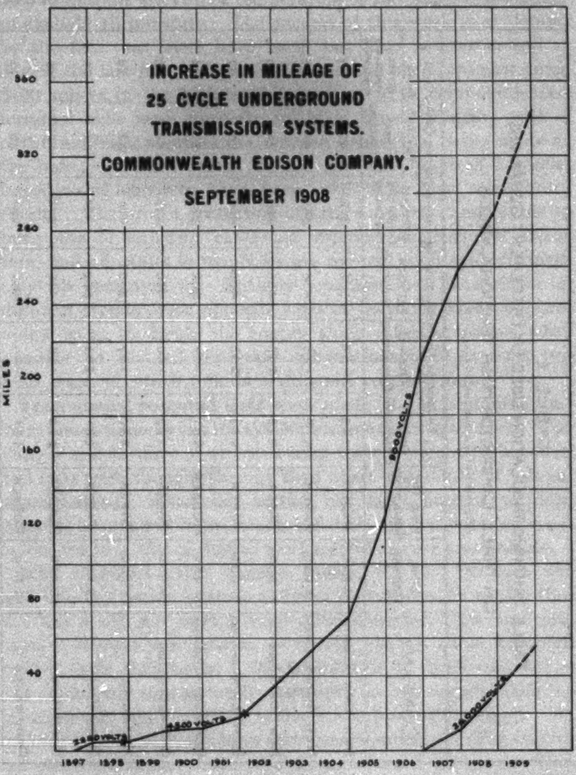

FIG. 3.

the sheath, in 1903 Mr. Burch* of Minneapolis made some interesting experiments. He found that it usually requires from a day to a week for the moisture to work down sufficiently to cause a burn-out. Paraffine had up to this time been used at the joints and in the terminal bells, but being hygroscopic in effect, due to voids left after cooling, it was not satisfactory at the higher voltage. About this time some of the engineers of the company, after considerable study and experimentation, de-

### TABLE I

### TABLE SHOWING INSULATION USED BY DIFFERENT COMPANIES ON THREE CONDUCTOR HIGH TENSION CABLES.

FROM PAPER BY W.G CARLTON IN 1902

| COMPANY | Line Voltage | Kind Of Insulation | Thickness Of Insulation In Thousandths Of An Inch | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Over 1 Conductor | Over 3 Conductors | Between Conductors | Between Conductors And Ground | Per 1000 Volts | |
| | | | | | | | Between Conductors | Between Conductors And Ground |
| New York-Edison | 6 600 | Paper | 156 | 156 | 312 | 312 | 47 | 47 |
| New York-Metropolitan | 6 600 | Paper | 218 | 125 | 436 | 343 | 67 | 52 |
| New York-Subway Co | 11 000 | Paper | 218 | 250 | 436 | 468 | 40 | 43 |
| Buffalo-Niagara Lines | 11 000 | Paper | 203 | 203 | 406 | 406 | 37 | 37 |
| Buffalo-Niagara Lines | 11 000 | Rubber | 281 | — | 562 | 281 | 51 | 25 |
| Chicago-Edison | 9 000 | Paper | 203 | 140 | 406 | 343 | 44 | 38 |
| Milwaukee | 15 000 | Paper | 250 | 187 | 500 | 437 | 33 | 29 |
| Saint Paul | 25 000 | Paper | 281 | 203 | 562 | 484 | 22 | 19 |
| Saint Paul | 25 000 | Rubber | 218 | 156 | 436 | 374 | 17 | 15 |
| Providence | 12 500 | Rubber | 281 | — | 562 | 281 | 45 | 22 |

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* Burch, A. I. E. E. Trans. 1903, page 433.

veloped a high-grade insulating compound which since then has been used exclusively on all high-potential work.

The splices are made up with great care and the compound is poured into the sleeve at a temperature of 150° cent. in a manner to exclude all moisture. The success of this work is evidenced by the fact that there have been but two failures in splices during the last five and one-half years and there are now some 3400 splices in the high-tension system. The compound-filled terminal bells were formerly made of brass cylinders with a cast-brass base, a substantial ground connection being made at the base. On some recent work a few bells made of a special impregnated concrete have been used with very satisfactory results. The proper protection of cables against damage due to burn-outs of adjacent cable has received considerable attention, and all cables in manholes are covered with split vitrified-clay tile cemented in. Entirely separate duct lines, either on different streets or on opposite sides of the same street, are provided, so as to divide the energy along different routes when possible, so that all important sub-stations have at least two lines, each of which follows a different conduit route.

Semi-annual potential tests were made at the beginning, but were discontinued when the system became more extensive. The danger and liability of accident from these frequent high-potential tests were thought to more than offset the doubtful advantages derived. Since then testing has been limited to new, altered, or repaired cable, which before being put into service is subjected to a test of double working voltage for one minute.

The record of cable trouble (Table II) for the last five and one-half years' operation shows that failure of cables thus far has really not been a very serious matter. The line protective devices are now so perfected that a cable burn-out causes little disturbance. Of the total of 44 cases recorded in the table, only four seriously disturbed the system, and each one of these was aggravated by faults in the protective relays. We believe that these faults have now been eliminated. The records of other companies have also been reported as good. Thus the New York Edison Company[1] in the nine years (1898 to 1907) during which its cable system grew from three to 200 miles had a total of 66 burn-outs, of which 38 were due to external causes, 18 at or in splices, 4 in bends, and 6 in the cable proper. The Cataract Power & Conduit Company of Buffalo[2] had a total of four burn-outs in seven years (1899 to 1906) on 12 miles of three-conductor rubber-covered cable operating at 11,000 volts; two were due to mechanical injury, one in a splice, and one in the cable. The rubber surrounding each conductor has a thickness of 9/32 in. and there is no overall jacket. The rubber shows no deterioration. Mr. Mershon[3] mentions four three-conductor cables, each about two-thirds of a mile long, operating at a pressure of 22,500 volts, on which there had been but one

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[1] Torchio, A. I. E. E. Trans. Dec. 1907, page 1711.

[2] W. S. Clark, A. I. E. E. Trans. 1906, page 209.

TABLE II

SUMMARY OF CABLE BURNOUTS

JAN. 1903* TO JULY 1-1908

9000 VOLTS

| YEAR | MILES OF CABLE DEC. 31. | BREAKDOWNS | | | | |
|---|---|---|---|---|---|---|
| | | IN JOINT | IN BEND | IN CABLE | EXTERNAL CAUSE | TOTAL |
| 1903 | 54 | 1 | | 3 | 4 | 8 |
| 1904 | 71 | | | 2 | 1 | 3 |
| 1905 | 125 | | 1 | 1 | 1 | 3 |
| 1906 | 209 | 1 | | 2 | 2 | 5 |
| 1907 | 254 | | | 4 | 3 | 17 |
| 1908 | JAN. 1 264 | | 1 | 3 | 4 | 8 |
| TOTAL | | 2 | 2 | 15 | 25 | 44 |
| 20000 VOLTS | | | | | | |
| 1907 | 11 | | | | 1 | 1 |
| 1908 | 11 | 1 | | 2 | – | 3 |
| TOTAL | | 1 | | 2 | 1 | 4 |

* DURING THE FIRST YEAR'S OPERATION AT 9000 VOLTS IN 1902 THERE WERE SEVERAL BREAKDOWNS IN JOINTS AND IN BENDS BUT THE TROUBLE RECORDS, UNFORTUNATELY, ARE NOT ENTIRELY COMPLETE.

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[3] Mershon, A. I. E. E. Trans. 1904, page 610.

case of trouble in three years and that at a poorly made splice. The terminal bells on these cables are made of hard rubber.

On the 20,000-volt line in Chicago, which has now been in service about 15 months and which was an initial installation at this higher pressure, there have thus far been a total of four burn-outs, one of which was due to a mechanical injury, one to moisture in a poorly made joint, and two were in the cable itself.

*Investigations.* It will be seen, therefore, that the experience with high-potential cable has not been such as to cause alarm. The most frequent sources of trouble are from without, and of these electrolysis is apparently the most persistent. However, with rapidly growing systems the destructive effect and danger of breakdowns tend constantly to increase, and it becomes advisable to forego complacency for a while and to look into the system with inquisitive eyes to see just what is going on.

It was this desire to know more about possible dangerous potential rises, so that proper safeguards against them could be provided, if found necessary, that led the Commonwealth Edison Company to undertake a series of spark-gap and oscillograph investigations, the principal results of which thus far obtained are described in this paper. A further purpose of the tests was to obtain information regarding these high-voltage systems for use in their further development. The investment required for such 20,000-volt and higher transmission cable system is very large; it therefore becomes all the more imperative to know that such investment is a safe one commercially.

*Tests on* 9000-*volt system.* About a year ago a series of oscillograph tests was started on the 9000-volt system to determine whether or not resonance existed in any part of it, or if dangerous potential rises occurred from any other cause. The oscillograms obtained were taken at the Fisk Street station and included current and pressure waves for all principal switching operations, as well as several for a special cable connection in which resonance was sought. None of the records showed any appreciable excess voltage.

These investigations were later continued and expanded, but no dangerous rises were found. Spark-gaps were installed at four different points of the system and their record carefully kept. The gaps consisted of needle points in series with which were resistance and fuse. They were connected between each phase and ground. These spark-gaps showed that there are frequent rises of about 70%, and occasional ones of about 100%, which apparently have no connection whatever with any switching. These occurred at the station and also in remote sub-stations. At times of cable breakdown, one or more of the spark-gaps invariably discharged at double potential[1]. With grounded systems cables break down first between a phase conductor and ground. When the protective devices fail to act properly, as happened occasionally before recent improvements were made,[2] the arc continues until it is communicated to one or both of the other phases. The effect on the system is then far more severe. Such occurrences were, however, the exception rather than the rule. When, during a breakdown, one or two of the spark-gaps discharge it is on the phase or phases other than the one on which the burn-out occurs. Sometimes all three of the gaps discharge during cable trouble, but not simultaneously. It is quite probable that the potential rises evidenced by these discharges are due to magnetic effect in the generators as much as to surges in the cables. There was only one case of cable breakdown which seemed clearly the result of a surge. During some arrangements which were being made at Fisk Street station to put a potential test on a bus-bar, one of the test leads accidentally came in contact with a live switch stud, the door over which had been opened. This grounded one phase of the system through 50 ft. of heavily insulated No. 12 wire in series with the high-tension coil of a dead 150-kw. testing transformer. The heavy insulation was punctured in a number of places and the entire 50 ft. of test conductor was vaporized. No other damage was done in the station. A few seconds later one of the cables burned out at a point about one mile from the station.

The net result of this investigation indicates that at the present time the 9000-volt system is reasonably free from dangerous conditions, as far as destructive potential rises are concerned. It also indicates the advisability of continuing to make tests on newly installed or repaired cable at double potential for one minute.

*Tests on* 20,000-*volt line.* Attention was then turned to the new 20,000-volt line in the attempt to learn what difficulties are to be met with there. On the diagram of this line in Fig. 4 are shown the locations at which current and pressure connections were made for the oscillograph. The numerals on the oscillograms refer to the corresponding ones of Fig. 4. Spark-gaps were connected to ground at points marked s.g. These spark-gaps were first installed in the Evanston sub-station at the end of the line and originally set at 1.1 in., corresponding to 21,700 volts. During fifteen days *A* phase discharged eight times, *B* phase five times, and *C* phase six times. Five times during this period two gaps discharged at the same time (four on *B* and *C*

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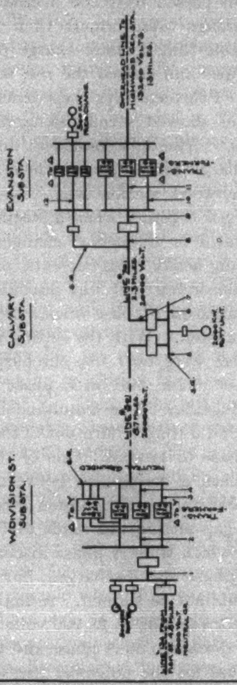
[1] Double potential when units with no neutral resistance were grounded, and about 130% over potential when neutral was grounded through resistance (R = 2.6 ohms).

[2] June paper A. I. E. E. Chicago, R. F. Schuchardt.

FIG. 4

SUBSTATION CONNECTIONS OF 20000 VOLT LINE SHOWING POINTS AT WHICH OSCILLOGRAMS WERE OBTAINED


W. DIVISION ST. SUBSTA.
CALVARY SUBSTA.
EVANSTON SUBSTA.
Δ TO Y
Δ TO Δ
TRANSFORMERS
NEUTRAL GROUNDED
S.G.
LINE 321 .67 MILES 20000 VOLT
LINE 321 2.3 MILES 20000 VOLT
OVERHEAD LINE TO HIGHWOOD GEN. STA. 13200 VOLTS 13 MILES
2000 K.W. ROT. UNIT
1
2
3
4
10
11
12

S.G.-SPARK GAP

▭ - OIL SWITCH.

RECORDS OF OSCILLOGRAPH TAKEN AS FOLLOWS:-

1. PRESSURE FROM SECONDARY OF POT. TRANS. ON A-B PHASE. 80 VOLTS.
2. CURRENT FROM SECONDARY OF CURR. TRANS. ON B PHASE.
3. PRESSURE FROM 11000 VOLT BUS A PHASE TO GROUND THROUGH 147000 OHM RES.
4. PRESSURE FROM 11000 VOLT BUS B PHASE TO GROUND THROUGH 147000 OHM RES.
5. PRESSURE FROM SECONDARY OF POT. TRANS. A PHASE (RATIO [illegible]) 55 VOLTS.
6. PRESSURE FROM 11000 VOLT BUS B PHASE TO GROUND THROUGH 147000 OHM RES.
7. PRESSURE FROM 11000 VOLT LINE CONDUCTOR B PHASE TO GR. THROUGH 147000 OHM RES.
8. PRESSURE FROM 11000 VOLT LINE CONDUCTOR B PHASE TO GR. THROUGH 147000 OHM RES.
9. PRESSURE FROM 11000 VOLT BUS B PHASE TO GROUND THROUGH 147000 OHM RES.
10. PRESSURE FROM SECONDARY OF POT. TRANS. (RATIO [illegible]) FOR PHASE SEE FIGS 7 TO 18 INCLUSIVE.
11. CURRENT FROM SECONDARY OF CURR. TRANS. FOR PHASE SEE FIGS 7 TO 18 INCLUSIVE.
12. CURRENT FROM SECONDARY OF CURR. TRANS. B PHASE.

and one on *A* and *B*). All other discharges were on one phase at a time. On only one day were there more than one discharge per phase, and on that day *B* and *C* phase gaps discharged together twice, the interval between the discharges being 18 min. With the exception of a single discharge on *A* phase, none of the discharges could be connected with any switching or other apparent source of disturbance. In this single case a heavy lightning storm passed over the overhead transmission line, which is fed through transformers from the 20,000-volt line. It seems probable that a static charge passed from the line into the transformer and caused the rise which discharged on the *A* phase gap. Fourteen days' experience with a gap of 1.15 in. (22,500 volts) showed seven discharges on *A* phase, six on *B*, and five on *C*. The only coincident disturbances were as follows: one discharge on *A* phase when a steam-driven generator at the Highwood station was " synchronized "; *B* and *C* phases discharged together when a steam-driven unit in parallel with a generator or frequency changer in Evanston governed poorly, causing heavy cross-currents; one discharge on *A* phase when a steam-driven unit was disconnected at Highwood, and one discharge on *B* phase when a steam-driven unit was shut down in Evanston. With the setting increased to 1.2 in. (23,300 volts) there were only five discharges recorded in four months, one on *A* phase, two on *B* phase alone, and one on *B* and *C* phases together. The simultaneous discharge on *B* and *C* phases occurred during a burn-out of the line, probably a breakdown of *A* phase to ground. One of the *B*-phase discharges took place when a connection between the 9000-volt coils of the *C* phase transformer at Division Street burned out. A further increase in gap setting was made to 1.25 in. and left for six weeks, during which time *A* phase discharged when the line broke down. *B* phase also discharged, but the connection with a disturbance could not be learned. A final increase to 1.3 in. was made. This corresponds to 25,000 volts. During three months there was one discharge on *A* phase and two on *C* phase, but here again no cause for the potential rises could be ascertained. Spark-gaps were also installed at the step-up end of the 20,000-volt line in the West Division street sub-station during a test at that point. They were set at 1.1 in. and during the few hours that they were connected each of the phases discharged heavily at different times. Recently spark-gaps were installed at the Calvary sub-station. They are set at 1.1 in. and each phase has discharged heavily at times.

An attempt was made with the oscillograph to determine the relation between the potential rises and operating conditions. The oscillograph was connected at various times at the three switching points of the line and some records were obtained for switching operations. Unfortunately the time during which the line could be kept out of service for these investigations was so limited that only a few records could be obtained for each operation. It is recognized that in such a limited number (and especially where, as in most cases, only one phase pressure could be recorded) many disturbances may have escaped detection. However, many of the curves are of considerable interest and may serve to bring out more discussion. A number of them are therefore included in this paper. It will be noted that none of the oscillograms shows potential rises as high as those recorded by the spark-gaps. Had more oscillograms been taken, or had all phase pressures been recorded simultaneously, higher rises might possibly have been observed. However, the function of the spark-gap is clearly to detect high potentials, while that of the oscillograph is to show the character of the disturbance and its duration. The spark-gap watches the line continuously, while the oscillograph records occurrences for but very brief intervals.

In the following Figures the source of energy is always from the left, the opening or closing operation being performed on the switch marked *S*. There being but one oscillograph and no pressure wires available, the records at the different sub-stations were not taken simultaneously. The apparatus was set up at one place and curves were obtained for the various operations. The apparatus was then moved to the next sub-station and the operations were repeated.

Fig. 5 is for closing and opening line No. 501. The current wave in the upper curve is the characteristic exciting current wave of a transformer when first energized. The logarithmic curve due to hysteresis is clearly shown. The dying of the pressures in comparatively slow oscillations when the line and transformers are disconnected is shown in the lower curves.

Fig. 6 gives curves for closing and opening line No. 701. A record obtained back at Division street for this operation at Calvary sub-station is given in the upper curve.

The next curves, Fig. 7, are for closing and opening the entire 11 miles of 20,000-volt line from Division street to Evanston. Curves of pressure were also obtained at the Calvary sub-station.

Fig. 8 shows curves for closing dead transformers on to a live bus-bar. The first rush of current in this case was nearly six times full-load current. An interesting curve is the one for West Division street showing the duration and amount of the current rush. The curve obtained on opening the switch to the transformers is also given.

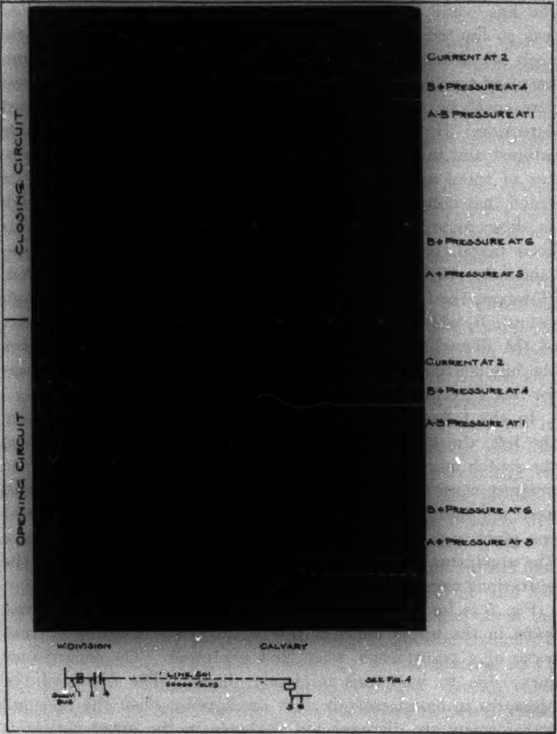


Fig. 5.

Line No. 701 was closed and opened with the transformers connected at Evanston, and the curves for these operations are given in Fig. 9. Records were also obtained at Division street for the closing operation and are shown in the upper curve.

The same operations were performed with the entire 11 miles of line, the records being given in Fig. 10.

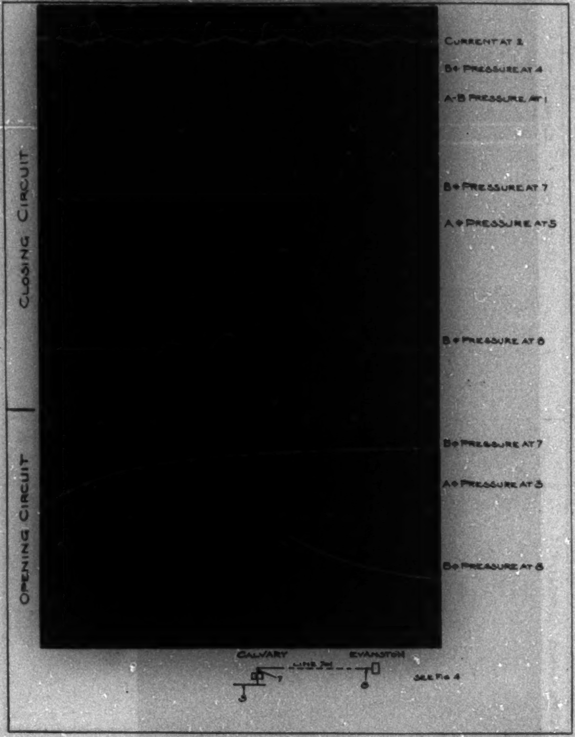


Fig. 6.

The motor of the frequency-changer set at Evanston is wound for 9000 volts, the line pressure being stepped down in three 200-kw. transformers. In Fig. 11 are shown curves obtained when closing these transformers to a live bus-bar. In the

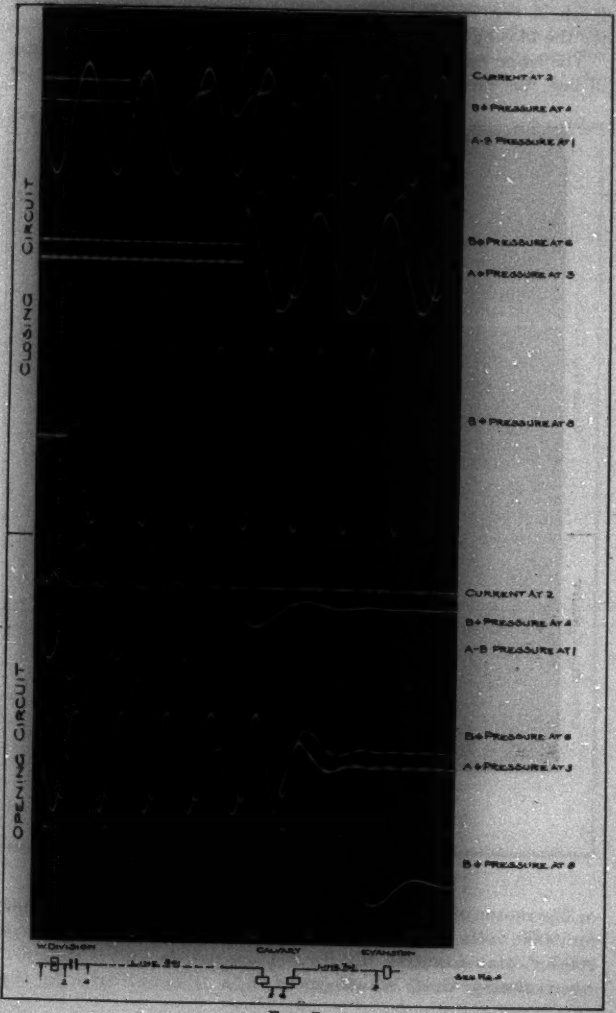

CLOSING CIRCUIT
OPENING CIRCUIT
CURRENT AT 2
B+PRESSURE AT 4
A-B PRESSURE AT 1
B+PRESSURE AT 6
A+PRESSURE AT 5
B+PRESSURE AT 8
CURRENT AT 2
B+PRESSURE AT 4
A-B PRESSURE AT 1
B+PRESSURE AT 6
A+PRESSURE AT 5
B+PRESSURE AT 8
W. DIVISION
CALVARY
EVANSTON
2
4
8

FIG. 7.

upper curve the transformers had previously been demagnetized by keeping them connected to the motor while being shut down until it had come to rest, the fields being kept excited. In the lower curve they had been disconnected at full pressure. The difference in current rush emphasizes the advisability of keeping the transformers connected to a dying machine when shutting down. This applies also to transformers of synchronous converter sets.

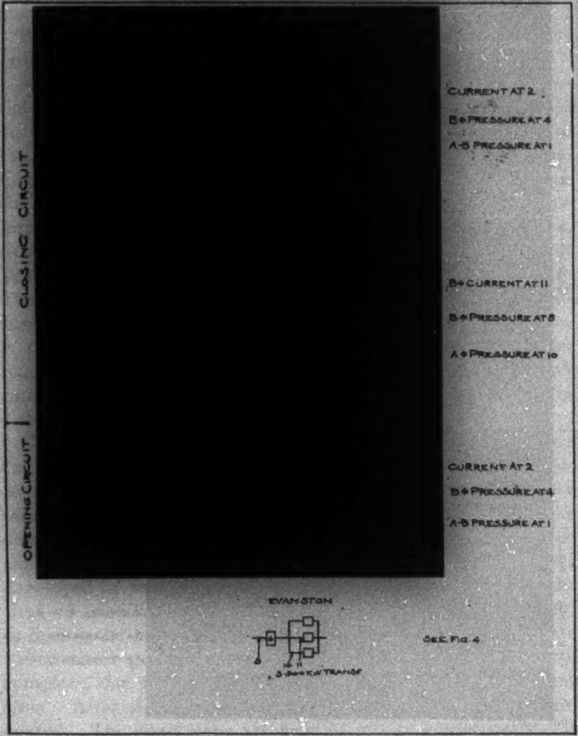


FIG. 8.

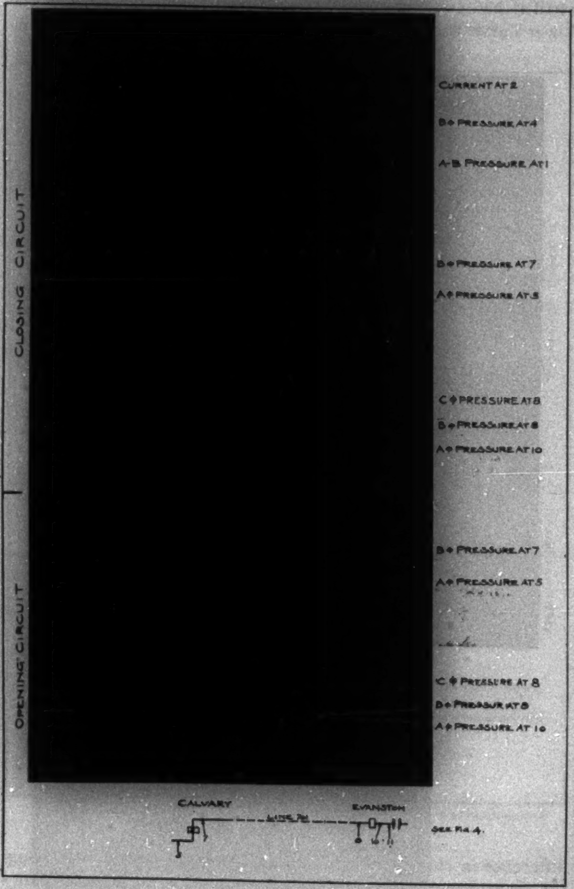

CLOSING CIRCUIT
OPENING CIRCUIT
CURRENT AT 2
B Φ PRESSURE AT 4
A-B PRESSURE AT 1
B Φ PRESSURE AT 7
A Φ PRESSURE AT 5
C Φ PRESSURE AT 8
B Φ PRESSURE AT 8
A Φ PRESSURE AT 10
B Φ PRESSURE AT 7
A Φ PRESSURE AT 5
C Φ PRESSURE AT 8
B Φ PRESSURE AT 8
A Φ PRESSURE AT 10
CALVARY
LINE 7H
EVANSTON
SEE FIG 4.

FIG. 9.

The curves for starting the frequency-changer set from these transformers, Fig. 12, show no potential disturbance.

Two load-curves are given in Fig. 13, taken at Division street. The conditions were as follows: upper curve, volts 9000, amperes 85, kilowatts 600, power-factor 45%; lower curve, volts 9000, amperes 105, kilowatts 1600, power-factor 97.5%.

Fig. 14 shows curves obtained at Evanston when a steam-driven generator at Highwood was " cut in " with the line.

At the Evanston sub-station there are three 200-watt potential transformers connected in star with their neutral grounded on both primary and secondary. It will be remembered that the 20,000-volt line is grounded solid at the Division street transformers, but at no other point. The oscillograph was placed in the neutral connection to ground of the Evanston potential transformers' primary and a current of 76 milliamperes was obtained, this amount remaining unchanged even when a resistance of 10,000 ohms was placed in series with the ground connection. The impedances of the three transformers have not been measured, but their load is not balanced. In Fig. 15 this current wave is shown taken simultaneously with pressure. The wave for phase-to-phase pressure shows an unstable condition. A summary of the results shown by these oscillograms is given in Table 3.

*Conclusions from investigations.* From the spark-gaps on the 20,000-volt line we learn then that pressure-rises in excess of 100% occur occasionally. The oscillograms thus far obtained give no clear evidence of the cause, but the cable broke down three times in 15 months, two of these times in the cable itself, either as a result of these rises, or of weakness developed by mechanical stresses imposed upon the cable at the time of installation. This record is reasonably satisfactory, as during the first year's operation we must expect to eliminate the weakest points. The second 20,000-volt line which will complete this northern ring is being installed at the present time. After it is put in service the investigation will be repeated. The spark-gaps are kept in service continuously. If dangerous potential rises still exist, the remedy will be applied, which, in the form of the aluminum arrester, is fortunately at hand. It is therefore quite prudent to state that 20,000 volts is a safe pressure for an underground system. Whether a higher voltage will be possible, is a matter which has received and is receiving considerable attention.

*Possible future developments.* The awakened interest in and

## TABLE III

### SUMMARY OF DISTURBANCES SHOWN ON OSCILLOGRAMS

FIGURES 5 TO 15 INCLUSIVE

| CIRCUIT TESTED | | | STEPUP TRANSF. AND LINE #501 | STEPUP TRANSF. AND LINES No. 501 AND 701 | LINE #701 ONLY | LINE #701 AND 3-300 K.W. TRANSF. | STEPUP TRANSF. LINES No. 501 & 701 AND 3-300 K.W. TRANSF. | 3-200 K.W. TRANSF. | | 3-500 K.W. TRANSF. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | DEMAGNETIZED | NOT DEMAGNETIZED | |
| CLOSING SWITCH | AT SWITCHING POINT | BUS PRESSURE | SLIGHT OSCILLATION | 12 % DROP | SLIGHT RISE | SLIGHT OSCILLATION | DROP | NO RISE | NO RISE | 15 % DROP |
| | | LINE PRESSURE | SLIGHT OSCILLATION | 50 % RISE | OSCILLATION FOR TWO ~ | 35 % RISE | 36 % RISE | NO RISE | NO RISE | 15 % DROP |
| | | CURRENT | 127 % | 140 % | — | 300 % | 200 % | 200 % | 500 % | 600 % |
| | AT INTERMEDIATE POINT | PRESSURE | — | 40 % RISE | — | — | 50 % RISE | — | — | — |
| | AT RECEIVER END | PRESSURE | 40 % RISE | 50 % RISE | OSCILLATION FOR THREE ~ | 10 % RISE | SLIGHT OSCILLATION | — | — | — |
| | | CURRENT | — | — | — | — | 400 %. | — | — | — |
| OPENING SWITCH | AT SWITCHING POINT | BUS PRESSURE | NO EFFECT | NO EFFECT | SLIGHT OSCILLATION | SLIGHT OSCILLATION | — | — | — | 18 % RISE |
| | | LINE PRESSURE | DIED DOWN IN COMPARATIVELY SLOW OSCILLATIONS WHERE TRANSFORMERS WERE CONNECTED TO LINE. WHERE LINE ONLY WAS OPENED, A SLIGHT PRESSURE RISE OCCURRED AND THE LINE THEN DISCHARGED THROUGH THE HIGH RESISTANCE OF THE OSCILLOGRAPH CIRCUIT. | | | | | | | |
| | AT RECEIVER END | PRESSURE | | | | | | | | |
| CURVES SHOWN IN | | | FIG. 5. | FIG. 7 | FIG. 6. | FIG. 9. | FIG. 10. | FIG. 11 | FIG. 11. | FIG. 8. |

growing demand for a "City Beautiful" mean the ultimate removal of smoky chimneys, dirt producing factories, and in some cases, of overhead lines from within the heart of the city. This will increase the demand for a means of economically transmitting energy underground in large quantities, and in many cases for comparatively long distances. When that time comes, and the herald has already appeared above the horizon, the operating companies will ask of the manufacturer a cable successfully to withstand the higher pressures required for the service.

Another condition which brings about a demand for high-voltage transmission is the better efficiency at present obtainable from large generating units in large stations, compared with small units in small stations. Recent improvements in turbine design are resulting in greatly decreased steam consumption, especially for smaller units. With a sufficiently high transmission voltage, however, it will in many cases be found cheaper to generate large quantities in a large station and transmit to the distant center where the load is comparatively small, than to generate in a smaller station at that center.

Regarding the maximum cable voltage, Mr. E. J. Berg in his new book on "Electrical Energy" (page 50) says:

> With the present state of the art it would not be conservative to use a cable at more than say 25,000 volts between conductors although it is to be expected that at least with rubber covered cables, or cables with insulation of varying specific inductive capacity a much higher voltage can finally be used.

Mr. H. G. Stott stated in 1906 in a paper on "Underground Cables",* that in his opinion cable voltages of 44,000 could be used, provided the neutral of the system were grounded, thus limiting the potential to ground to 25,000 volts. Cables have been made which in the factory have successfully withstood pressures as high as 80,000 volts or more for an hour, but they have not yet been made for commercial use at such pressures. In the *Elektrotechnische Zeitschrift* of July, 1907 (page 676) appeared an abstract of a paper by de Marchena discussing pressure limitations for cables in which he made the interesting statement:

> As at very high pressures, potential rises are expected to occur less frequently than at low standard pressures, the factor of safety could be

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* Read before the American Street & Interurban Railway Engineering Association, Oct., 1906.

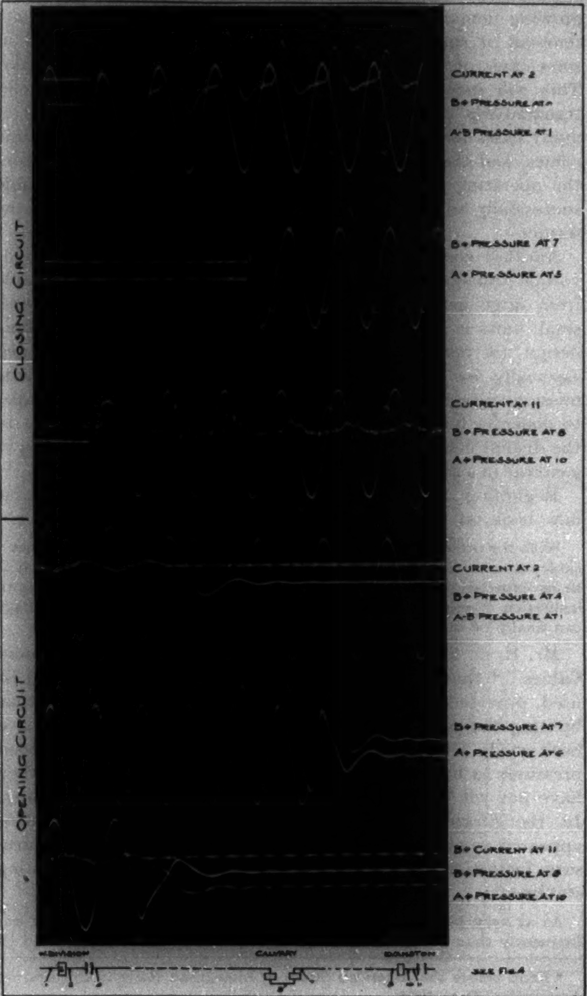
CLOSING CIRCUIT
CURRENT AT 2
B+ PRESSURE AT 4
A-B PRESSURE AT 1
B+ PRESSURE AT 7
A+ PRESSURE AT 5
CURRENT AT 11
B+ PRESSURE AT 8
A+ PRESSURE AT 10
OPENING CIRCUIT
CURRENT AT 2
B+ PRESSURE AT 4
A-B PRESSURE AT 1
B+ PRESSURE AT 7
A+ PRESSURE AT 6
B+ CURRENT AT 11
B+ PRESSURE AT 8
A+ PRESSURE AT 10
W. DIVISION
CALVARY
EVANSTON
SEE FIG. 4

FIG. 10.

**decreased so that cables for a standard pressure of 40,000 volts may be manufactured especially for shorter distances.**

It would be of interest to know de Marchena's reason for this statement. Messrs. Feldman and Herzog in the *Elektrotechnische Zeitschrift* for December, 1907 (page 1163) cite many cases of cable installations for voltages over 10,000 and some over 20,000, and also mention the very severe tests to which these cables were subjected. The general subject of high-tension transmission by underground cable is ably discussed from the manufacturer's standpoint by Mr. Richard Apt, Technical Director of the Berlin Cable Works (A. E. G.) in the *Elektrotechnische Zeitschrift* of Feb. 1908 (page 159). Single-conductor, concentric, and three-core cables are discussed, as well as the relative merits of different insulating materials and of aluminum for single-conductor cables. Mr. Apt prophesies that the single-conductor cable for very high pressures is the cable of the future. The installation for the County of Durham Electrical Power Distribution Co. Ltd., England, where about 40 miles of three-conductor cable was put into service for the first time for 20,000 volts, is described. The cable is imbedded in troughs filled with an asphaltum compound. Telephone and pilot wires are placed under the trough. It is stated that this is the method generally employed in England for laying cables.

B φ Current
B φ Bus Pressure
B φ Bus Pressure on Pot. Transf. Secondaries
B φ Current
B φ Bus Pressure
B φ Bus Pressure on Pot. Transf. Secondaries

Fig. 11.

If we interpret the discussions of American cable engineers aright, they concur with Mr. Apt in his prophecy regarding single-conductor cable. The heating of the dielectric due to electrostatic stress, with consequent weakening of insulation, the critical voltage which no practical thickness of insulation will withstand—these and other conditions limit the stress to which insulation can safely be subjected. With single-conductor cable in a three-phase system the line pressure can thus be $\sqrt{3}$ times the maximum safe cable pressure. A thin wall of high dielectric strength is desirable to lessen heating and to keep the cable from being too large and too stiff, but then the corona effect due to highly concentrated electrostatic stress must be considered and guarded against. Asphaltum troughs certainly guard against electrolysis and also insulate the lead sheaths of adjacent cables from each other. These sheaths should of course be grounded at one end. It is possible that the commercial demand for underground cables at voltages from 30,000 to 40,000 will result in the use of single-conductor cable, possibly embedded in asphaltum.

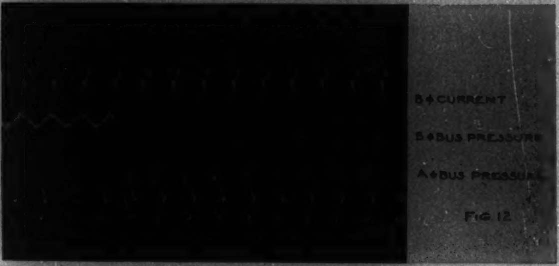

FIG. 12.

With the increasing popularity of all-the-year country life and with the spread of communities as mentioned in the beginning of this paper, it is not hard to imagine a time when it may in exceptional cases be desirable to put some cross-country lines or parts thereof under cover. The general dependance on electrical energy and the immense investments at each end of these transmissions may in special cases justify a fairly large expenditure, provided a very reasonable assurance of reliability is obtained. As many of these lines will be operating at pressures beyond the reach of underground cables, it is possible that a recently suggested protected bus-bar construction may be used. Such a construction could follow the general surface of the land and be built on a right-of-way in conjunction with a railway. The art of insulator manufacture will undoubtedly advance so that pressures of 200,000 volts or more could be employed, if conditions should ever demand such pressures. This construction appears to obviate many of the shortcomings of present high-tension cable systems.

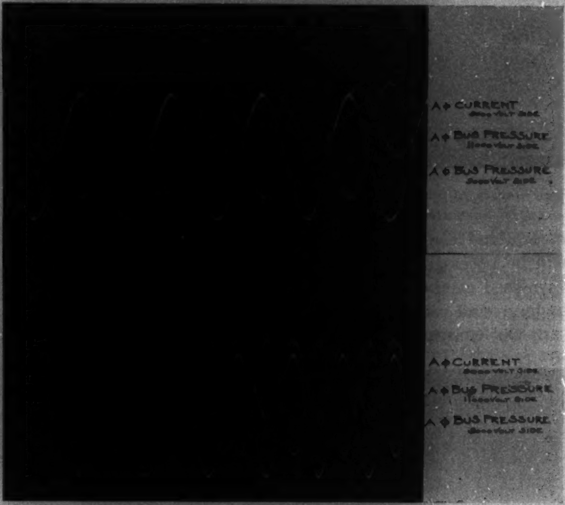

FIG. 13.

## SUMMARY

From the viewpoint of the investor or operator the state of the art regarding high-tension underground transmission might be summarized as follows:

1. Underground cable systems of 11,000 volts and under, if properly made, installed, and operated, will give at least equally and probably more reliable service than most of the other elements in the electric power system of which the cable system is a part.

2. Where local and commercial conditions justify, pressures as high as 25,000 volts can be satisfactorily used even for systems aggregating as much as a hundred miles of cable. No single line of such a system would be much longer than twenty miles. If higher voltages are needed to meet operating requirements, and can be justified commercially, special construction will be necessary to overcome limitations in paper, rubber, or varnished cambric insulation, and also in the standard forms of underground conduit or subways used in this country.

FIG. 14.

3. On comparatively short lengths, underground or under water, as a part of a long overhead transmission line, cables operating at 40,000 volts can be used.

FIG. 15.

4. Potential rises of 50% and 100% are not uncommon in large underground cable systems, although this fact may not always be manifest, due to high factor-of-safety.

5. Definite knowledge of what actually occurs in large high-potential underground systems is still meager, especially regarding intensity and frequency of surges, heating effects, and critical temperature for various kinds and thicknesses of insulation, corona effects, and similar matters.

In conclusion we would urge all companies having high-potential cable systems to keep a complete and systematic record of all troubles. To quote Dr. Steinmetz:

> To determine the origin and cause of high voltage disturbances, so as to be able to guard against their recurrence, the most important thing seems to be to very carefully observe and record all the details of the phenomena, even those which appear unessential. The existence of static on switchboards, lines, etc., and the existence of voltages and currents different from those which may be expected, require special attention. Either of these is sufficient to raise the suspicion of some dangerous fault in the system or some dangerous arrangement of apparatus, which requires consideration . . . The severity of the phenomena depends almost entirely upon the power momentarily available in the system and very rapidly increases with the size of the generating stations. With the increasing power and extension of electric systems we must expect to see these disturbances increase in destructiveness. The prospect which this holds out for the future is not very agreeable; it shows, however, the increasing importance for the operating engineer to study and become familiar with the subject, so as to be able to cope with the problems which are before him, which perhaps are the most serious in the field of electrical engineering . . . It would therefore be a great help if a far closer interchange of experience existed between different operating engineers.

May we not urge on all engineers to remember these words and to appreciate how, by following Dr. Steinmetz's bidding, we all can help to advance the art.

## ADDENDUM

*Spark-gaps.* In using spark-gaps as a means for measuring potentials, certain precautions must be taken to insure reliable results. This fact is, of course, well known. The spark-gaps mentioned in the paper were made up on the usual insulated standard and provided with ordinary No. 5 sewing needles. The series resistance consisted of carbon rods, of an amount to limit the current to about one-half ampere at normal pressure. In order to get the correct interpretation for the various settings, the conditions of humidity and temperature of the places where the spark-gaps were installed were duplicated in the laboratory and the gaps were repeatedly calibrated from 0.4 to 1.3 in. gap.

Within this range they were found to agree to within about 2% of the Institute Standardization Rules. It is safe to assume then that the indications recorded in the paper are correct within 5%, which is well within the accuracy required for this work.

Where the spark-gaps are in continuous service, to detect occasional high rises it is necessary either to renew the needles daily, or to brush the points frequently to avoid an accumulation of dust which would alter the effective gap-distances. Any tight enclosure around the gap to prevent this accumulation would introduce errors due to the ionization of the enclosed air. During a discharge the needle points burn to a bead, the size of this bead being an index of the severity of the discharge, and thus roughly of the intensity of the disturbance at that point. A recording meter is placed in series with the gaps to record the time of the discharge.

*Oscillograph.* The development of a successful portable oscillograph marked an important step in the development of cable systems. It afforded a means for studying the system analytically, so that causes for possible unstable conditions could be determined and guarded against. In the particular application of detecting voltage rises of short duration its usefulness, while still very great, is more limited. The time-interval, already mentioned in the paper, introduces an external limitation. The limitations of the apparatus itself are principally as follows:

1. The free periodicity of the vibrators is less than that of some occasional waves of very short length. In the oscillograph used in the test the vibrators were adjusted for their highest free periodicity, about 6,000 cycles per second. Any peak having a periodicity higher than this would not be correctly recorded. However, a peak of such extremely short duration would have too little energy to cause a harmful disturbance and would thus be of little interest.

2. The vibrator cannot be made absolutely dead-beat, but fair results are obtained with five parts of castor oil and one part of turpentine as the damping medium.

3. The self-induction of the vibrator circuit is not entirely nil, but is sufficiently low to be practically negligible.

4. The sensitiveness of apparatus cannot be made perfect, and its degree of perfection in this regard determines the degree of accuracy of its indications. The amperes per millimeter of deflection of the three vibrators used is from 0.00518 to 0.00578,

While in these four important qualities the oscillograph does not attain the ideal, yet for all practical purposes the apparatus is quite satisfactory. The limited time-interval of application is the most serious shortcoming, and probably the cause for the absence of double-potential peaks on the curves. A great number of oscillograms could be taken and yet none of them happen to coincide in time with a high peak. This was actually the case in the tests made, during which there was never a spark-gap discharge simultaneous with the taking of an oscillogram.

## DISCUSSION ON "HIGH-POTENTIAL UNDERGROUND TRANSMISSION." NEW YORK OCTOBER 9, 1908.

**President Ferguson:** The subject for discussion this evening, gentlemen, is not only interesting from a scientific standpoint, but is of great importance commercially, because of its possible influence upon the investment and methods of operation of our large lighting and power systems.

With the concentration of the production of electrical energy, with its attendant advantages of lower initial investment and of increased economy in operation, which seems to be the order of the day, there naturally follows the necessity for higher voltages. This demand is coming now not only from the country districts, where water power exists, but also from the more congested districts, such as our great cities where immense power houses have been established to supply not only the lighting, power, and railways of the cities themselves, but also of the suburban area for many miles around.

With the increase in values of property in the centers of our large cities, there comes a gradual expansion of the congested areas and with it, in the interest of public safety, a limitation in the use of overhead construction, especially for high-tension transmission lines, and we find ourselves facing the necessity of placing them underground.

Although a great deal of thought has been given to the subject of overhead high-tension transmission, there appears to be much less definitely known regarding high-tension underground transmission, possibly because the necessity for such knowledge has not previously existed. The possibilities of the future are so great and the trend of the times so marked that it appears the subject before us is a timely one, and it would seem very important that all operating companies supplying energy in bulk should investigate the matter thoroughly and give it much serious thought, since a knowledge of the conditions existing may result in great saving in investment and greater reliability in operation.

It is with the idea in view of bringing out such knowledge as may be available and impressing upon those interested the importance to them of assisting in the development of the work that the paper of the evening is presented to you.

**Charles H. Merz:** Those of us who, by periodical visits to the states and by meeting American engineers when in England, have been able to keep in touch with American progress, have always been much impressed by the development and distribution of electrical energy in large cities in the States.

High-potential underground transmission has been used in such cases, but in the outlying districts it is perhaps not incorrect to say that underground transmission has only recently commenced to take the place of overhead transmission. The fact that a large proportion of the work hitherto has been in crowded and congested districts probably explains why a "draw-in" or "conduit" system has been, so far as the writer is aware, generally adopted for underground transmission in the United States in preference to the so-called "solid" system of laying cables, largely in vogue in England, or armored cables which are used almost exclusively on the Continent of Europe and also largely in England. The extension of underground transmission to outlying and less congested districts will probably result in the merits of these other two systems of laying transmission cables being considered. It may be of interest to refer briefly to these different systems of laying cables and to some considerations affecting the layout of the cable network in such districts.

For congested districts, such as are met with in the centre of all large cities, the "duct" system is often the only practicable system because it is impossible to take up the streets frequently to lay further cables or to carry out repairs. Accessibility to the cables is, however, some would say, the only advantage of this system for, when laid in this way, the lead of the cables is probably more exposed to deterioration by electrolysis and chemical action than in either of the other two systems referred to above. Further, the system is expensive, especially if the manholes are really substantially constructed and if proper precautions are taken to prevent a fault on any one cable interfering with the other cables. It is also probable that the carrying capacity of the cables for a given section is somewhat less than with either of the other two systems, due to the bunching together of a large number of cables in a confined space and the presence of air between the cable and the duct, which must interfere with the transfer of heat from the cable. This latter point is influenced, of course, to a great extent by the number of ducts laid together and the arrangement of the ducts relatively to one another.

In the so-called "solid" system the cable is laid in an earthenware or wooden trough sufficiently large to allow, say 0.75 in. clearance all round the cable, which space is filled with bitumen, pitch or some similar substance. The trough is covered by 3 in. brick or tile.

According to the writer's experience, the solid system in either earthenware or wooden troughs is the cheapest of the three systems mentioned. In saying this it is assumed that armored cables are only permissible if the lead and armoring are effectively protected from moisture, etc. This necessitates not only a sufficient number of wrappings between the lead and the armor and outside the armor, but also effective impregnation of these coverings with some waterproof and insulating composition that will not crack when the cable is bent and which will retain its qualities. An efficiently armored cable costs, laid in the ground, in England from 5 per cent to 10 per cent more than a lead-covered cable laid on the solid system, but it would seem fair to say that an armored cable which is made and finished in the factory, where proper supervision is possible, should have a longer life than cables laid either on the solid system or drawn into ducts. The solid system has, however, proved an extremely efficient system in practice if care is taken in the composition of the material used for filling in the troughs, so that in this country, at any rate in outlying districts, it works out somewhat cheaper than a thoroughly well designed and manufactured armored cable, and it will no doubt continue to be largely used for such purposes.

Apart from the question of life of the lead, which, as far as present experience goes, is the same thing as life of the cable itself, the accessibility of the conduit system is of little or no advantage in outlying districts. In the writer's opinion it is of little advantage anywhere except in the most congested districts, for the following reasons:

1. It is more expensive, even if there are several ducts laid together and all ducts contain cables.
2. It is much more expensive in initial capital expenditure if spare ducts are laid.
3. Apart from the question of the greater security of supply, if mains are laid by different routes it does not pay in most cases to lay more than one cable by the same route; for it is obvious that if it is a question of supplying any given large area with power, the more the cables can be distributed along different routes the greater will be the number of power ,users that can be supplied without large expenditure on branch cables.

The question of the most economical arrangement of network is one that grows in importance as the area to be supplied increases. In congested districts where very large powers are dealt with from one sub-station situated within a relatively short distance of the generating station, it is frequently only possible to deal with the load by means of a radial system; that is, a system in which several mains, one or more of which are spare, run from the generating station to each sub-station. When, however, it comes to a question of distributing power over wide areas and in outlying districts, a radial system in which two or more cables, one of which is a spare, are laid by the same route to each sub-station, becomes very expensive and it is necessary to consider higher voltages and the use of so-called "ring mains." The use of high voltage also enables the most economical section of copper to be used. This economical section, according to the writer's experience, is in general somewhere between a 0.1 sq. in. and a 0.15 sq. in. cable (say 125,000 circular mils and 190,000 circular mils) for three-core cables; that is to say, it is more economical in first cost per kilowatt transmitted to transmit a certain amount of power by means of a cable of this section working at a sufficiently high pressure to enable it to carry the required quantity of power than by any other section or voltage. This, of course, arises solely on account of the fact that the smaller cable can be worked at a considerably higher current density for the same temperature rise. In congested districts where it is impossible to avoid the use of several cables on the same route to a sub-station fed direct from the generating station, it would be more economical, if armored cable or cables laid on the solid system were used, to lay a relatively large number of cables of the economical section rather than a smaller number of cables of the larger section working at the same voltage. If a conduit line be used, however, the number and size of cables are decided more by the total quantity of heat that a block of cables so laid can radiate than by any other consideration; and for the sake of simplicity and to reduce losses and heat generated, the tendency will be to keep down the number of ducts and increase the section of the cable to 0.25 sq. in., or even more, with a corresponding increase in the total cost per kilowatt capacity. This is a further argument in favor of armored cable or cables laid solid.

If the network be made up of ring mains, the power may flow in either direction along any individual cable and it is not possible automatically to isolate a length of faulty cable by means of automatic cutouts of the ordinary overload and reverse-current type. According to the writer's experience, however, any difficulty in this direction can be got over by the use of some form of balanced relay system.* With this device faulty lengths of cable can be instantaneously cut out without any interference with the system or with synchronous plant running thereon, and without interrupting the supply to any consumer, however many sub-stations may be connected to the ring main, and, what is perhaps more important, there is no danger of a section of the system that is not faulty being also cut out.

This system has acted in such a satisfactory manner in actual practice that it is now being adopted largely both in this country and abroad for protecting all kinds of cable systems, whether laid out as ring mains or on the radial system.

Experience in the north of England shows that a 20,000-volt underground cable system may be installed with assurance that it will work well. In the counties of Northumberland and Durham there is now nearly 100 miles of such cable in use. The cables are three-core paper cables lead-covered and laid on the solid system in earthenware troughs; they are made to stand a test pressure of double the working pressure after laying and jointing, and short samples of the cable are specified to stand in the factory pressures of four times the working pressure after bending tests have been applied. There is also a very

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*For further details of this system see *Electrical Review* (London,) August 28th, 1908, and the *Elektrotechnische Zeitschrift*, dated 19th and 26th March, and 2nd April, 1908. (Paper by Herr Kuhlmann).

large mileage of 12,000-volt and 6,000-volt cable working in conjunction with the 20,000-volt system. In cables for extra-high-tension work the joints have generally been found to possess the lowest factor of safety, and it is well worth while devoting special attention to their design so as to provide ample margin in insulation to cover indifferent workmanship on the part of the jointer, and to make sure that after laying, the cable and not the joints would break down if a sufficiently high pressure were applied.

Spark-gaps are installed at each end of each cable length. At special points, such as where overhead lines join the cable system, water resistances are installed, thus providing a path for any surges that may occur under working conditions.

Experience has proved that there is no more trouble with such a system than with a 5,000-volt system. On several occasions consecutive lengths of 20,000-volt cable connected in series to form a single length of over 20 miles have been switched on, but in no case has there been any evidence at the spark-gaps or elsewhere of any excessive pressure. Cables directly connected to a large step-down transformer at the farther end have also been switched on without trouble. 11,000-volt overhead lines and cables have been working in series on the same network for some time without any dangerous surging. In some cases when faults have occurred in 20,000-volt joints, the automatic cut-outs have been found to isolate the fault before the compound in the joint has become thoroughly carbonized, and it has been necessary to close the switches and allow them to operate again several times before the localization tests could be applied. This treatment must subject the system to heavy rushes of current, but there has been no evidence of dangerous surging in the pressure which could not be taken care of by the spark-gaps, etc.

**H. W. Fisher:** Though the results of the tests given by the authors indicate what voltages cables may be subjected to under working conditions, yet I think it must be admitted that under other working conditions similar tests might have shown quite different results. It is, therefore, highly desirable that other operating companies should make similar tests covering a long period of time and present the results before the Institute. When this is done a better idea of the conditions producing maximum voltage stress can be obtained.

The authors have not specified clearly what they mean by double working voltage, for with a grounded neutral the voltage to ground on the 20,000-volt lines would be 11,550 volts. This doubt impels me to ask if the voltage applied between conductors and ground is $2 \times 11550 = 23100$ volts, and that between conductors, 40,000 volts? If these are the voltages applied, the test to ground is not sufficient, because in some cases the spark-gap method gave over 25,000 volts. I would suggest two and one-half times the working voltage as a figure that is more in keeping with tests made on other large installations of cables in New York City and elsewhere, as it is to the interest of both manufacturer and operator to have the assurance that the cables in question can withstand for five minutes two and one-half times the working voltage without failure or injury to the dielectric.

I presume that the 11,000 volts mentioned several times at the bottom of Fig. 4 should really be 11,550 volts, the electromotive force to ground on a 20,000-volt circuit with the neutral grounded.

With cables operating at extremely high voltages, limitations in duct size, test of cable, and the possibility that impulsive rises of voltage are proportionally less than with lower voltages, may make a double working voltage test sufficient.

Statements made in the paper convey the impression that a good insulating compound is the all-important feature of cable joints. I believe that the method of joint construction is the first and most important consideration; after this work is done well, the use of any good insulating compound of proved merit with fairly high melting point, a compound which does not in compounding with the insulation of the cables themselves form an inferior mixture, will insure perfect joints. It should be remembered that the insulating of the individual conductors is a matter which almost necessarily and unavoidably varies with the workmen. I have found that by standardizing joint-making by the use of properly prepared paper tubes of suitable size and composition, I am able to insure at least the necessary minimum thickness of insulation at all points. In my experience this plan works out better than where the thickness and tension under which insulating tapes are applied by individual workmen are left to individual judgment. I understand that such tubes were used on the cables referred to by the authors.

In one of the foot-notes I see that the voltage rise was 30 per cent more when the neutral was grounded through 2.6 ohms. Was this increase due to a distortion of the electromotive force wave curve by increasing the ratio of maximum to mean effective volts? I have obtained this effect, but only when the series resistance was high.

It is interesting to note that the voltage did not rise when the circuit was opened. This I suppose was due to the fact that oil circuit-breakers open at or near the zero part of the electromotive force wave. I have frequently obtained rises of voltage by opening a switch which made an air arc when operated.

The authors say that "asphaltum troughs certainly guard against electrolysis." I must take exception to this statement, because the worst cases of electrolysis I have known were on cables laid in troughs filled with asphaltum. If a cable could be perfectly protected from moisture by asphaltum, I admit that electrolysis would not occur, but this is scarcely possible, and at the moist spots the electrolysis is greatly accentuated causing pit holes in the lead. I know of cases where thousands of feet of cable laid in asphalt troughs were completely destroyed by electrolysis. While it may seem desirable to insulate the lead covers of cables, it must be remembered that when these cables are of the single-conductor type and carry alternating currents these induced voltages between the lead covers may be considerable. I have obtained from 15 to 30 volts per 1000 ft. with an ordinary lead-covered cable, and in the case of a steel-wire armored cable the lead volts per 1000 ft. were 100. The lead volts per 1000 ft. on the same kind of cable armored with two wraps of steel tape were 350. From this it is evident that at least in the case of armored cables, the armor and lead should be connected frequently, especially as the lead current may be as high as 80 per cent of the conductor current, and this is of sufficient magnitude to cause destructive alternating-current electrolytic action if the current be concentrated at isolated points. Fortunately, in practice the sheath of armored cables is generally continuously grounded.

The thickness of insulation on the 9000-volt cables is given but it is not given in the case of the 20,000-volt cable.

**H. G. Stott:** I recently passed through Buffalo, and I was interested to inquire about the history of certain cables which I put down there in 1891. They were rubber-covered cables, $\frac{4}{32}$ in. rubber, with lead jacket, and put down to carry 60-light arc circuits, having approximately 3000 volts pressure. I found that they are using these same cables to carry 100-light enclosed arc lamp circuits of 7500 volts. As these cables are now 17 years old, the permanency of the investment seems to be very gratifying. Other cables, I think 0000 copper size, which were purchased and put down at the same time, 17 years ago, for use on 1100 volts, having also $\frac{4}{32}$ in. rubber insulation with lead jacket, are to-day carrying 2500 volts, and are said to be the best cables they have.

Referring to Table I, the first column shows the year, and the second the miles of cable. It will be noticed that after the first 2 years the miles of cable are a little more than doubled. The first 2 years apply to the cables of the Manhattan Elevated Railway, and subsequently they apply, from 1904 on, to the subway cables also. For the last 3 years there have been over 350 miles of 11000-volt cables in service. Following along the first year there will be found a classification of the troubles, which shows a total of 7 burn-outs, due to various causes, one of which was due to a surge. The last column, excluding external causes and damages due to crowbars, etc., gives the number of burn-outs per 100 miles of cable per annum. In the first year there was considerable trouble with the joints, but there was only one fault in 122 miles of cable, and there were only 4.01 burn-outs per 100 miles, due to all internal causes.

In the second year, 1903, there were four breakdowns due to surges. Dr. Steinmetz has expressed an opinion on what probably took place,* and concluded that these surges probably caused a rise of potential of 120,000 volts, so that an 11,000-volt cable can not be blamed for breaking down under these conditions.

**TABLE I.**

High-Tension Cable Breakdown Summary

Jan. 1902 to Oct. 1908.

11,000 Volts.

| Year | Miles of cable | In joint | In bend | In cable | | External causes | Total | Excluding external causes and surges per year per hundred miles |
|---|---|---|---|---|---|---|---|---|
| | | | | Faults | Surges | | | |
| 1902 | 122 | 3 | 2 | 1 | 1 | | 7 | 4.01 |
| 1903 | 144 | 2 | | 1 | 4 | 1 | 8 | 2.09 |
| 1904 | 330 | 1 | | 1 | | 1 | 3 | 0.61 |
| 1905 | 351 | | 1 | 2 | | | 3 | 0.85 |
| 1906 | 353 | 3 | | 3 | 1 | 4 | 11 | 1.70 |
| 1907 | 353 | 1 | | | | 5 | 6 | 0.28 |
| 1908 | 368 | 1 | | | | 4 | 5 | 0.28 |
| Total | | 11 | 3 | 8 | 6 | 15 | 43 | |

Note.—

External Causes { Mechanical injury. Steam leaks. Armor burns from other cables.

The number of burn-outs per 100 miles of cable per annum has fallen during the last 2 years to 0.28, or practically one fault per 400 miles of cable per year. That is a reassuring record; when our overhead transmission lines can show anything like it, we can look forward to reliable long-distance transmission.

Fig. 1 is an oscillograph record taken, which shows the turbine generator running on the circuit. No. I is the voltage on phases 1 to 2, 10,000 volts; No. II is No. I phase to neutral, 5780 volts; No. III is neutral to ground.

Fig. 2 shows the same machine simply switched on to 38.3 miles of cable. This is rather an interesting record. No. 1 is the potential wave, No. II is charging current to cable phase 1, and No. III charging current to cables through neutral There is a very pronounced ninth harmonic it amounts probably to seven per cent of the fundamental. That was a revelation, as we had no idea that any such harmonic as that existed, and we are going to make further investigations. I think it also illustrates the point that further investigations on underground cables will probably yield great rewards for our trouble.

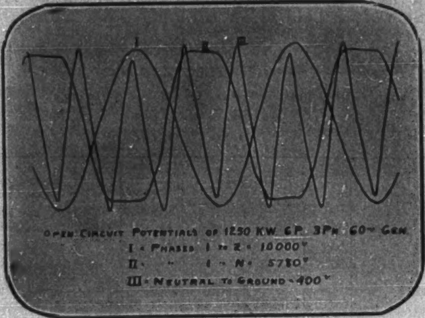


FIG. 1

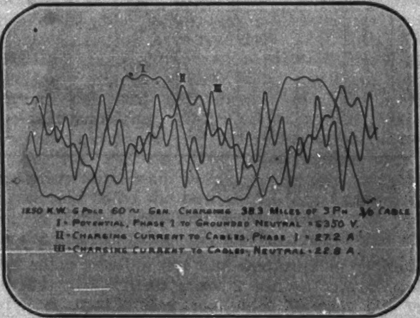


FIG. 2

Mr. Merz is a distinguished engineer of very wide experience, but I think that we should apply his conclusions with great caution. Two systems, absolutely similar as to cables, capacities, inductance, etc., but having widely different amounts of power connected, may act in entirely different ways. A system absolutely harmless with perhaps a couple of thousand kilowatts connected to it, may become subject to the most destructive surges and phenomena of all kinds when 100,000 kilowatts are connected to it. In the particular case of the Interborough system, it is possible to develop more than 300,000 kw. on short-circuits between stations. In Mr. Merz's system there are comparatively small and scattered stations, as I understand, so in our American plants there is an entirely different set of conditions.

An apparatus which is going to help out materially in the development of large power plants is the induction type of generator. We cannot, I believe, go on adding indefinitely to the capacity of synchronous generators in one plant. We will soon reach a point where the short-circuit current will be so great that it will be absolutely impossible to take care of it by any automatic apparatus. We all know that in the case of a bad short-circuit on a large system the time-element relays and reverse-current relays fail to act selectively, and everything goes out. With the induction generator, however, we can add on to our present plants indefinitely without increasing the short-circuit current, as the induction generator has the peculiar characteristic of practically ceasing to generate under short-circuit conditions.

**E. J. Berg:** This paper gives a clue to the probable maximum voltage for high-potential cables. This clue is more discernable when the results obtained by the authors are compared with those obtained in similar tests recently made by Mr. W. F. Wells and myself on the Brooklyn Edison Company's system. In these tests the voltage was 6,000 instead of 9,000, and the neutral was not grounded. We also found from spark-gap indications that under apparently normal conditions double voltage existed at times. These abnormal voltages occurred relatively seldom, perhaps once in a week, or once in two weeks, whereas with the 9,000-volt cables in the Chicago system these abnormal voltages took place every day; and in the case of the 20,000-volt system they found them much more frequently. From this it seems reasonable to conclude that the difficulties due to abnormal voltages will increase with the cable voltage, as should indeed be expected, since a large part of the available energy is stored electrostatically and is proportional to the square of the voltage. Beyond question, commercially a 20,000-volt cable system seems perfectly practicable, the question is how much higher can the pressure be raised.

At the St. Louis International Congress in 1904 Mr. Jona read a paper on cables, discussing the dielectric strength of various insulating compounds and insulators, in general. If I remember correctly, he stated that the maximum permissible potential gradient at the surface of the conductor, using rubber as insulator, was 300,000 volts per inch. Assuming that to be correct, it is possible to calculate the limiting voltage for a given size conductor. Calculations show that it would not be practicable to use small conductors at 20,000 volts and above. At 40,000 volts quite large insulators would have to be used even if the insulation were of the very best.

With large conductors, it would be hardly practicable to make three-conductor cables, they would be unwieldy; consequently single-conductor cables would be used. With single-conductor cables, difficulties may be anticipated, since there is considerable losses in the lead if the lead is grounded, and if the lead is insulated it is subjected to considerable voltages. However, these voltages are proportional to the current, and the losses to the square of the current, and the current will be relatively small at 40,000 volts, so that these difficulties may not be serious.

The authors mention the large current taken by transformers in switching. The oscillograms show six times normal full-load current; that is, perhaps sixty to one hundred times the normal exciting current or the current which would flow after a second or two. This abnormal current depends upon the magnetic condition of the transformer and the phase of the impressed electromotive force at the time the switch is closed. In general, the lower the saturation under normal operation the less instantaneous current. If the density of the iron in the transformer were 65,000 lines per square inch, double voltage could be applied without saturating the iron. Thus such transformers would not be saturated when closed to a circuit of normal voltage even if the phase relation of the electromotive force were most unfavorable, assuming that the residual magnetism were small. With such transformers the maximum current would no doubt be less than full-load current. They would, however, require from 30 to 50 per cent more iron, and would therefore cost more. This construction would not be warranted unless great advantages were gained. These advantages would be: first, small current, which often is of little value; secondly, small mechanical stresses on winding which may be of advantage. So far I have been unable to locate any large stresses, but they undoubtedly exist.

**Wallace S. Clark:** The authors say that in a grounded system—I presume they mean star-connected—with the neutral grounded, the burn-outs take place to ground. That is not necessarily so. It happened in this case because: first, the insulation to ground is less than that between conductors; secondly, the cable is paper-insulated, and the usual cause of failure of paper-insulated cable is some injury to the lead. It is probable that the burn-out would go to earth, but if the cable had the same thickness of insulation to lead that it had between conductors, it is possible that surges would also have caused some rise of potential between phases, and might have caused a burn-out between conductors.

I do not think that the putting of high voltage periodically on cables for the purposes of tests does the cable any good; it does not show anything, and it is no assurance that the cable tested that way will not burn out the next day or the next hour. Insulation tests are perhaps a little better made periodically. Furthermore, with the present tendency to make paper cables with very low insulation resistance, it is rather difficult to get good results from such tests. There is however, one form of inspection which is greatly needed, the inspection for electrolysis.

If the same amount of money were invested in watching for electrolysis, as in periodic high-tension insulation testing, just as many burn-outs would probably be avoided.

That with a star-connected circuit neutral grounded about seven-tenths of the insulation between conductors is all that is needed to ground, seems to be more of a theory than a fact, because the potential rise noted in this paper seemed to be to ground, to be apparently double the working potential between conductors, and a good deal more than double the working potential to ground. The overcoming of this condition would really be of tremendous economical importance, because it would mean a very much cheaper cable for a given service.

There is one feature in practically all types of cable installations that has not been referred to; that is, the cable that is tested for five minutes at two and one-half times the working pressure will easily stand for five seconds four times the working pressure. That the puncture is a factor, not only of the pressure, but of the length of time the pressure is applied, has been a boon to every cable installation in this country. Several years ago I made some tests to verify this. A few days ago, after reading Messrs. Junkersfeld and Schweitzer's paper I made similar tests, and these gave almost exactly the same results as those formerly obtained.

From the cable manufacturers' standpoint there is no hesitation about using 25,000 volts. But I do not think that it is practicable with any of the forms of insulation in use at present to make very small conductors for 25,000 volts satisfactorily. Furthermore, 25,000- and the 20,000-volt cables that are in use in this country are really working at a less factor of safety than most of the 11,000-volt cables.

I understand that the thickness of insulation in thousandths of an inch between conductors on the Chicago 9,000-volt cables is about 44, and on the 20,000 volt cables about 28 per 1000 volts. It is undoubtedly true that the 20,000-volt cables are made with more care, and probably with a higher dielectric strength in the insulating material, but I doubt if that is enough to make up for so great a difference in thickness of insulation per 1000 volts, so it must be acknowledged that these cables are worked at a less factor of safety. This condition may be a justifiable one, because these cables are less important to the system than the 9,000-volt cables; if this is not so then the 9,000-volt cables have altogether too much insulation on them.

In the matter of cable economics, assume that there are two cables, a 25,000-volt cable and an 11,000-volt cable and that they will last almost exactly the same length of time. Then it is necessary to write off more money per year depreciation on the 25,000-volt cable than on the 11,000-volt cable because the copper for which scrap value can be obtained is the same. Assuming the scrap value of the copper at 15c. per pound for a 4/0, 11,000-volt paper cable, then there will be written off for whatever may seem to be the life of the cable, 66c. a foot on the 11,000-volt cables, and on the 25,000-volt cable about $1.19 a foot.

There are some other cables besides the ones mentioned by Mr. Stott which are running along peacefully under 11,000 volts pressure, and are just about as good as when they were installed in 1898. I think they are the oldest 11,000-volt cables in the country. Unfortunately these cables, as well as the cables Mr. Stott mentioned, are rubber-insulated and do not depend entirely on the lead covers. Just how long a lead-covered paper cable will survive is still undecided.

**Alex Dow:** In Detroit there are two cables operating regularly at 23,000 volts. Each cable is 39,075 ft. long. The cable conductor is 19-strand, equal to No. 2 B. & S. The insulation is $\frac{2}{32}$ in. rubber and $\frac{6}{32}$ in. of varnished cambric on each conductor, and $\frac{3}{32}$ in. varnished cambric over all, and $\frac{3}{32}$ lead sheathing. The lead sheath is sectionalized at every second manhole, between 700 and 800 ft., in order to prevent the travel along the lead sheath of stray railway return current. Each of these 700- and 800-ft. lengths of lead sheath is solidly connected to earth. One of these cables has been in service for 13 months. It is not the older of the two cables, but it is that which has the most continuous and useful history. It went into service September 4, 1907. Since that time it has broken down six times. One of these breakdowns was obviously due to high temperature from a nearby steam heating pipe. The other five are not attributable to any known cause; four of the breakdowns were in the cable itself, including the one due to the known cause; two of them were in joints. There were four to earth, and two between phases. Adding to this the experience had with the second cable, after it was rejoined, I may say that the total breakdowns were twelve, seven of which were in the joints and five in the cable. Seven were short circuits and five to earth. So that nothing seems to be proved.

The most notable observation is that the faults occur in the middle third of the cable, and are not accompanied by any great disturbances at the terminals. This seems to confirm the observation made by Messrs. Junkersfeld and Schweitzer, that such disturbances do not travel the entire length of the cable, but may spend their energy in one part thereof. Our conception which we will attempt to confirm or disprove by experiment, is that in a cable of that length, working at that frequency, connected in the way in which that is connected, the tendency is for such disturbances to attain their maximum in the middle third of the cable. A desirable precaution would be to cut the cable in the middle, looping it into a sub-station in that neighborhood which is available, and there connect it to electrolytic static dischargers. This will be done, and the action following thereon may be of interest to us, or it may not.

The joints of the first cable were originally insulated according to instructions received from the cable manufacturers by applying a straight wrapping of the varnished cambric tape. The three-conductor joints were wrapped over all and the sleeve filled with a compound. It was obvious to us that the compound used could not possibly penetrate between the layers of tape, and that it was not at all likely to penetrate thoroughly all the larger interstices between conductors. It did not, in fact. The joints broke down continuously from the time the cable was put in service. We stopped using it during the day, but operated it at 4600 volts during evenings as a reserve cable. During the day we made over again the one hundred and twenty-five joints. In the new making up of the joints we restored the rubber as nearly as might be, with the usual vulcanizing tape. We also restored the varnished cambric insulation, thoroughly painting each lap of tape with a non-drying varnish of the same kind as that used in making the cable. The result was satisfactory. The joints, placed on test in comparison with the original joints, showed that they could remain intact under a prolonged test of 30,000 volts. The original joints always broke down within a week or two. The cable put into service with these new joints proved as satisfactory as the other cable which had such joints to begin with.

Our conclusion, in addition to the one already given, is as follows. It is essential that the insulation of joints shall be solid and not include air, as air in the lapping sooner or later causes the joint to break down.

On emergency work and repairs made in a hurry we have used rubber and paper and paraffin. We admit that paraffin is not entirely satisfactory, but we have never had a breakdown which could be attributed to moisture in a paraffin joint, and there is no doubt that thoroughly boiled out paraffin has no air left in it. Whatever of shrinkage there is in the paraffin, is to all intents and purposes followed up and the joint is homogeneous.

Another conclusion is for a higher factor of safety to earth. It will be noticed that the over-all insulation is $\frac{3}{32}$ in. which is theoretically correct, with the grounded neutral. We think that there should be a higher margin of safety, and have adopted it on a third cable which is now going in.

Mr. Merz wants to put his cables down solid in asphaltum so that they will not be attacked by electrolysis. That is quite a common and doubtless a proper practice in England, but it is questionable whether it is worth while in America. Of late years we have adopted the practice of laying pavements on water-proof foundations. In almost all American cities, with a few exceptions, like New Orleans, the soil is under drained, so that the soil in which the conduits are laid is reasonably dry. Any one who has had experience with cables has noticed that in a street in which electrolysis was frequent, and failure of lead coverings common, the trouble has ceased as soon as the street was paved with a water-proof pavement. It is obvious that there is no electrolysis in dry soil, but perhaps there is no dry soil in England.

The system referred to by Mr. Merz is along the line of a distribution system, as distinguished from a transmission system. In none of our large systems, except perhaps the central districts of New York and Chicago, would the comments of Mr. Merz be quite applicable. The cables in Detroit and in most American cities go into sub-stations, from which the distribution is by overhead lines. Where cable distribution is required it is under conditions which call for radial distribution. Circular distribution, while occasionally called for, is not frequent. Therefore the comparison of English and American cable methods is not direct, but can only be indirect.

**Warren Partridge:** The experience of the Public Service Corporation of New Jersey with high-potential underground transmission when reduced to burn-outs per mile of cable per year has been considerably better than the 20,000-volt experience in Chicago, as reported by Messrs. Junkersfeld and Schweitzer, but when compared with the Chicago 9000-volt system, the results have been very much worse. The exact facts will be given, however, with the hope that they may help engineers of cable systems to tend toward the straight and narrow path where cables never puncture nor picks break through.

The essential facts of the Public Service system are as follows:

Marion Plant with 10,000 kw. in 25-cycle turbine units
and 6,000 kw. in 60-cycle " "
Coal Street plant with 9,000 kw. in 25-cycle engine units
City Dock " " 5,950 kw. in 60-cycle " "
and 3,000 kw. in 60-cycle turbine unit

The City Dock plant generates 2400 volts two phase and connects to the transmission system through 3000 kw. in transformers connected three-phase—two-phase Scott system. With this exception all generators are three-phase, 13,200 volts star wound. The neutral is not grounded.

Connected to the 13,200-volt bus-bars at Marion, Coal Street, and City Dock are twenty-one underground feeders, aggregating 81 miles of cable and two overhead feeders aggregating 65 miles of line. These cables and overhead lines feed nine 60-cycle sub-stations in which the greater part of the apparatus is composed of step-down transformers, and twelve 25-cycle sub-stations in which there are synchronous converters. The 60- and 25-cycle systems are independent except that some cables can be used on either service.

One cable is No. 4, four cables No. 1, while the remaining sixteen cables are 00. All are three-conductor, paper-insulated $\frac{7}{32}$ in. over each conductor and $\frac{7}{32}$ in. over all, giving 0.437 in. between conductors and between each conductor and ground. The cable sheath is $\frac{1}{8}$ in. lead and the majority of joint sleeves are paraffin filled, compound having been used on a few of the cables. The conduits are part fibre duct and part tile duct.

The record of cable troubles from January 1, 1905 to October 1, 1908, a period of 3.75 years, is as follows: breakdowns, in joints, 11; from external causes, 16; in the cables, 25; a total of 52. The total number of cable-mile-years is 255. Therefore the actual cable breakdowns not accounted for by external causes or by defective installation is approximately 0.1 per mile of cable per year.

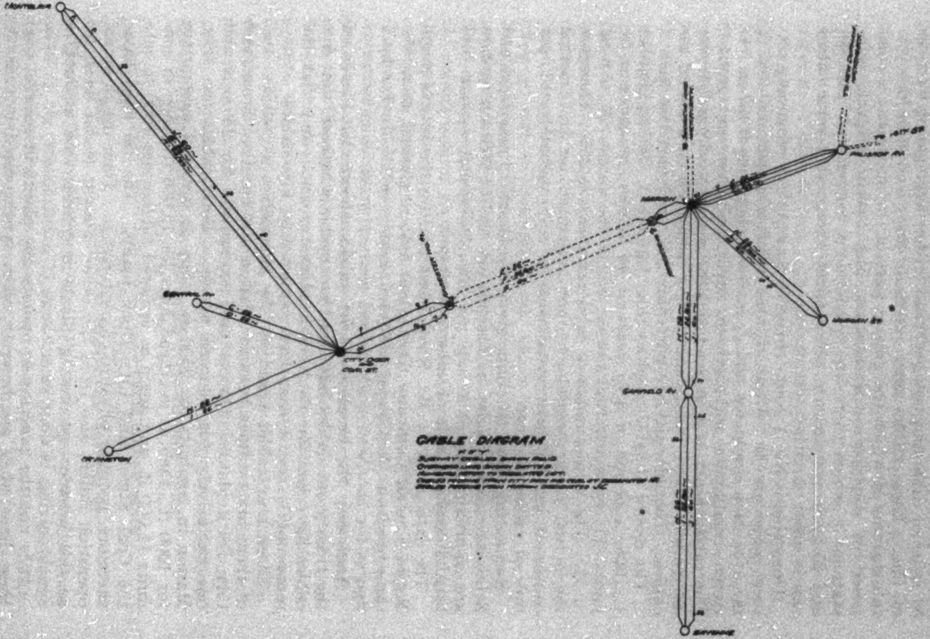
Estimating from the data given by Messrs. Junkersfeld and Schweitzer, the results in Chicago on the 11,000-volt system are approximately 0.02 and on the 20,000-volt system 0.14 breakdowns per mile of cable per year.

The data given by Mr. Rhodes last year for the Interborough Rapid Transit Company 11,000-volt system showed about the same results as the Chicago 9000-volt system, while Mr. Torchio's figures for the New York Edison were, I think, even better.

Analyzing the breakdowns by cables, shows that eleven of the twenty-one cables have had no trouble whatever, that five cables have had one each, two cables two each, and that the remaining sixteen breaks have occurred on four cables.

These four cables stand out by themselves as follows: two of them are tie lines between Marion and the Coal Street and City Dock plants. One is used exclusively for 25-cycle and one exclusively for 60-cycle service. Both cables run from Marion in conduits for 2500 ft., then as armored submarines for 1000 ft., then as overhead lines for 16,000 ft., then in conduits 11,000 ft. and again as armored submarines 1000 ft. into the Coal Street and City Dock plants. The tie lines have, therefore, peculiar physical characteristics. Their use in actual operation differs also from the other straight feeder lines, for as ties between generating plants a considerable amount of synchronizing is done over them.

It is not the practice to operate the plants in parallel over these lines; they are, however, often synchronized in order to transfer load from one station to the other without service interruptions. We know that some of the breakdowns over


CABLE DIAGRAM
KEY
GARFIELD AV.
MARION
CITY DOCK
COAL ST.

these lines have been due to synohronizing or rather to non-synchronizing and believe that others have been due to this same cause even when it was impossible to trace the sequence of events.

The other two lines that have a large number of burn-outs are both long lines, seven miles each, are both operated exclusively on 60-cycle service, and are both smaller than the standard 00 cable, being No. 4 and No. 1 respectively. One feeds from the Marion bus-bar and one from City Dock bus-bar. What the relation is between the above characteristics and the resulting burn-outs is hard to determine. Spark-gap and oscillograph records during different switching operations would undoubtedly throw some light on the subject and will be made later in connection with proposed installation of electrolytic dischargers.

Voltage surges of more or less severity have taken place a number of times on the system, as indicated not only by the cable punctures but by the wrecking of many sets of static dischargers and lightning-arresters.

In spite of all difficulties experienced we agree with the authors of this paper, that cable systems are fully as reliable as other elements in the electric power system. Our records for a period of three years show that cable breakdowns caused but 7 per cent of all the interruptions to service and that the duration of time of cable interruptions was no longer than the average for interruptions from other causes.

A quick summary of the essential differences between the Chicago system and the Public Service system might be made as follows:

1. Chicago, 9000 volts. Public Service 13,200 volts.

This condition is at once much more severe, being a voltage increase of nearly 50 per cent, and assuming a possible surge voltage of double potential would give a possible maximum of 26,400 against 18,000.

2. Chicago, essentially all underground feeders.

Public Service, a considerable amount of overhead lines operated in conjunction with the cable system.

3. Chicago, thickness of insulation per 1000 volts 0.44 inch between conductors and 0.38 in. between conductors and ground.

Public Service, thickness of insulation per 1000 volts 0.33 in. between conductors and between conductors and ground.

However, as thickness of insulation is not a direct function of voltage it is probable that the factor of safety of the two insulations is not radically different.

I would like to inquire what thickness of insulation is used on the 20,000-volt cables at Chicago, and whether ducts larger than standard 3 in. have been employed to carry these cables?

4. Chicago, neutral grounded.

Public Service, neutral not grounded.

There may be other differences between the two systems which would be evident to one more familiar with that of the Chicago system.

The above comparison is made, in order to give, if possible, some clue to the reasons behind the greater percentage of breakdowns that have occurred on the Public Service system.

**Breakdowns**
13,200-volt cable system

| No. | Date | Cable | External injury | Joints | Break-downs |
|---|---|---|---|---|---|
| 1 | 5- 7-05 | Nk. B | .. | 1 | .. |
| 2 | 7-16-05 | " E | .. | 1 | .. |
| 3 | 9-16-05 | " G | .. | .. | 1 |
| 4 | 10-22-05 | " E | .. | .. | 1 |
| 5 | 11-17-05 | " E | .. | .. | 1 |
| 6 | 12- 2-05 | J. C. A | 1 | .. | .. |
| 7 | 5- 4-06 | " E | .. | .. | 1 |
| 8 | 5- 7-06 | Nk. B | 1 | .. | .. |
| 9 | 7- 6-06 | " E | .. | .. | 1 |
| 10 | 7- 6-06 | J. C. A | 1 | .. | .. |
| 11 | 7-15-06 | " A | .. | .. | 1 |
| 12 | 7-17-06 | Nk. J | .. | .. | 1 |
| 13 | 7-19-06 | " A | .. | 1 | .. |
| 14 | 9-25-06 | " E | .. | .. | 1 |
| 15 | 9-29-06 | " F | .. | .. | 1 |
| 16 | 10-10-06 | " G | .. | .. | 1 |
| 17 | 10-20-06 | " B | .. | .. | 1 |
| 18 | 11- 4-06 | " E | 1 | .. | .. |
| 19 | 11- 4-06 | " F | 1 | .. | .. |
| 20 | 1- 5-07 | " G | .. | .. | 1 |
| 21 | 1- 7-07 | " G | .. | .. | 1 |
| 22 | 3-15-07 | " B | .. | 1 | .. |
| 23 | 3-27-07 | J. C. M | .. | .. | 1 |
| 24 | 3-27-07 | " J | .. | .. | 1 |
| 25 | 4-24-07 | " H | 1 | .. | .. |
| 26 | 5- 4-07 | Nk. G | .. | .. | 1 |
| 27 | 6-17-07 | " J | .. | 1 | .. |
| 28 | 6-17-07 | " G | .. | 1 | .. |
| 29 | 6-17-07 | " G | .. | 1 | .. |
| 30 | 8-24-07 | " E | 1 | .. | .. |
| 31 | 8-25-07 | J. C. M | 1 | .. | .. |
| 32 | 8-29-07 | " L | 1 | .. | .. |
| 33 | 8-30-07 | Nk. J | .. | .. | 1 |
| 34 | 9-16-07 | J. C. K | 1 | .. | .. |
| 35 | 9-21-07 | " M | .. | 1 | .. |
| 36 | 10- 5-07 | " H | .. | .. | 1 |
| 37 | 10-20-07 | " D | 1 | .. | .. |
| 38 | 1-20-08 | " J | .. | .. | 1 |
| 39 | 2-18-08 | " H | .. | 1 | .. |
| 40 | 4-22-08 | " M | .. | .. | 1 |
| 41 | 5-26-08 | " L | 1 | .. | .. |
| 42 | 7- 1-08 | " A | .. | .. | 1 |
| 43 | 7-14-08 | Nk. G | 1 | .. | .. |
| 44 | 8-16-08 | J. C. C | 1 | .. | .. |
| 45 | 8-20-08 | " J | .. | .. | 1 |
| 46 | 8-21-08 | Nk. J | 1 | .. | .. |
| 47 | 8-25-08 | J. C. C | 1 | .. | .. |
| 48 | 8-25-08 | Nk. J | .. | .. | 1 |
| 49 | 9-12-08 | " J | .. | .. | 1 |
| 50 | 9-13-08 | J. C. F | .. | .. | 1 |
| 51 | 9-13-08 | " G | .. | 1 | .. |
| 52 | 9-16-08 | " G | .. | 1 | .. |
| | Totals.......... | ............. | 16 | 11 | 25 |

Similar comparisons might be made with the systems of the New York Interborough and the New York Edison, with this difference: the New York Edison system is 6600 volts and the neutral is not grounded, while the Interborough is 11,000 volts and the neutral is grounded through resistance.

The fact that the Public Service voltage is higher than any of the above systems seems the most obvious explanation of the results, and the fact that the Chicago 20,000-volt figures are not as good as those from their 9000-volt system further bears out this conclusion; the answer being that as the voltage has been raised, the general factor of safety of cables, switching devices, protective apparatus, and the personal element of the operators, has lagged somewhat behind.

**E. E. F. Creighton:** All experience confirms the authors' statement that with rapidly growing systems the destructive effects and danger of breakdowns tend constantly to increase. There is a tendency to danger from another source which may be distinguished from that of mere increase of kilowatt capacity and mileage of cable. This danger is involved apparently in accidental coincidence of capacity and inductance with a surge frequency of harmonic when an accidental arcing ground takes place. There is a third condition, mentioned by the authors, namely, rises of potential when the circuit is operating normally. By normal operation is meant the absence of arcs between any phase and ground, or an isolated conductor. There is still a lack of complete experimental data, but I feel convinced that these three conditions outlined are quite distinct, although they may all exist simultaneously. Reviewing these conditions.

1. The troubles resulting from excessive power. A short-circuit of great power stores up electromagnetism which, if suddenly destroyed, produces excessive potentials. It is generally believed that arcs of thousands of amperes of alternating current have a tendency suddenly to interrupt the current. Incidentally, the excessive mechanical strains have a tendency to crack or otherwise injure insulation, combined with an accidental arcing ground.

2. The second condition is the old meace, resonance. That a mere increase in power and cable mileage may have less to do with the production of transient abnormal potentials was proved by some tests made by the writer in association with Mr. S. D. Sprong. The conditions of a cable system were such that the instantaneous value of the surges could be recorded with an oscillograph. Tests were made first with one cable, then we were surprised to find that the surges were less when a second cable was connected to the same bus-bar. When a third cable was added, however, the surges were again aggravated and increased in severity for every successive addition. The detailed results of these tests we hope to present later, when the work will be more complete.

3. The surges not generated by an arcing ground which travels around a circuit are surrounded with mystery. They are not directly connected with switching or accidental conditions, and by observation they frequently produce higher potentials on the system than accidental arcing grounds. The probable source of the oscillations is the arcs on the low-voltage circuit.

In some tests made several years ago on the system of the Detroit Edison Company operating under normal conditions we found potentials of 125 per cent every few seconds, potentials of 150 per cent to 175 per cent every few minutes, and potentials of over 200 per cent twice in one day.

It is not possible commercially to insulate every conductor from its adjacent conductor sufficiently to carry the maximum potential strains of the system. For example, a turn of a transformer normally carrying 10 volts cannot always be insulated to carry the line potential of say 10,000 volts, yet it is possible to get such a potential there. Fortunately such potential differences do not occur frequently in actual practice, and on the end-turns, where they usually appear, the insulation is exceptionally reinforced.

**L. T. Robinson:** In view of the reference to some limitations of the oscillograph used by Messrs. Junkersfeld and Schweitzer, and the accompanying statement that "For all practical purposes the apparatus is quite satisfactory," I do not feel that the remarks are entirely justified.

In reference to the free periodicity of the vibrators, it is quite possible to produce moving systems in which the current passes through the strips having a frequency of nearly double that which was used or, roughly, 10,000. However, this is accomplished at such a sacrifice of strength and size in the moving parts, that it is not desirable for industrial use. Further, with few exceptions any investigation that requires a frequency in the vibrators of over six or seven thousand would require a frequency of an entirely different order.

The authors say that the vibrators cannot be made absolutely dead beat. I feel that this must be due to a misunderstanding of what can readily be accomplished, as the tests on vibrators shown in Figs. 1 *a* and *b*, indicate over-damping in some instances.

It is true that the self-induction of the vibrator circuit can never be entirely nil. This is no less true of any circuit which can be arranged. The inductance of the vibrators themselves is so small in comparison with any arrangement of conductors which can be used to connect it to the circuit under test, that this limitation, if it has any real significance, does not relate specifically to the oscillograph. In fact it is quite possible that the vibrator itself, due to the action of the moving strips in the magnetic field, could be represented as a capacity rather than as an inductance; that is, the current through this circuit as far as the vibrator only is considered may possibly be leading by an imperceptible amount.

The sensitiveness of the apparatus can be improved somewhat, but if a different class of problems entirely are to be attacked a sensibility of an entirely different order is required, and the small amount which can be gained by sacrificing strength and dimensions of moving parts is not worth while. The limited time-interval of application, I believe, should not be considered a

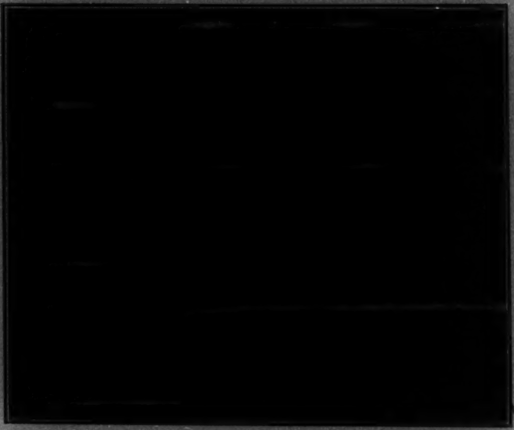


FIG 1.—*a*. Overdamping. →
Three vibrators using separate zero lines

FIG. 1.—*b*. Critical damping. Single vibrator. →

The time scale is such that the portions of records shown in *a* and *b* correspond to about 1.25 sec.

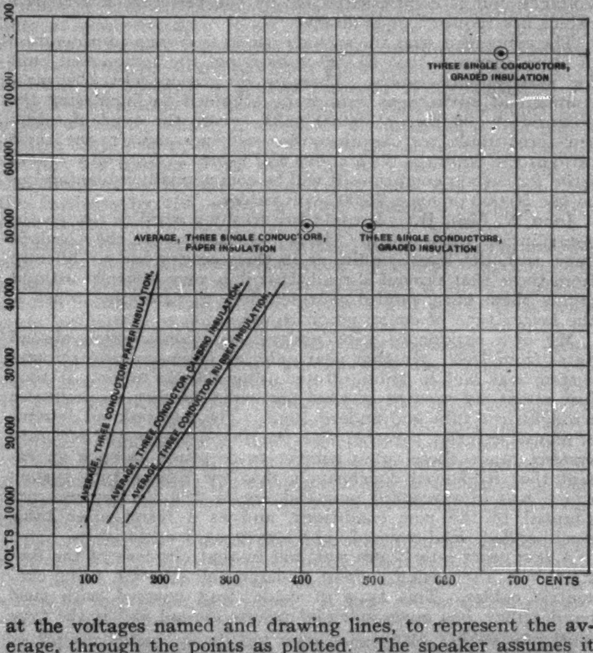
shortcoming at all. To meet conditions of continuous application for comparatively long intervals, special devices for moving a film to receive the image have been devised. They could easily be made and would, undoubtedly, be successful. The trouble here is not one relating to mechanical or electrical details, but to the fact that to operate a film continuously, of the usual width, and at speeds ordinarily employed, would cost about $500 per hour, a prohibitive amount.

I believe the reason why no spark-gap discharges were obtained simultaneously with the taking of an oscillogram was due to the fact that the potential rises represent a very small amount of energy. When the oscillograph is connected the discharge passes through it, thus preventing any rise of potential, and fails to record on the film, either because of its very short duration, or the very small current in the instrument at the time.

**Henry Floy:** The experience with 20,000 volts here cited and the testimony that could be adduced regarding 25,000-volt cables show that even at these higher voltages such cable is reliable. Above these potentials, we have, as far as I know, no commercial installations in this country. The authors have touched on the questions as to whether it is practicable, and whether commercial conditions will require in the near future, the use of cables at higher potentials. Some figuring has been done, particularly by engineers in England, tending to demonstrate that 25,000 volts is as high a potential as it will commercially and financially pay to use in connection with cables, indicating that if higher voltages are attempted the cost of the cables will be so great as to make preferable the installation of cables in greater number operating at lower potentials.

With reference to high-tension cables for alternating-current service, the manufacturing companies are ahead of the operating conditions; that is to say, the manufacturing companies have for years been ready to furnish cables for higher potentials than the operating companies were ready to use. For instance, at present it is possible to obtain, a cable designed for 75,000-volt operation, tested for a much higher potential; but I do not suppose that any one is quite ready to install a 75,000-volt underground distributing system, although possibly such cables could advantageously be used at the end of an aerial line or under water where special conditions require special construction.

As regards the commercial, financial, and practical use of higher tension cables; that is, those designed for potentials above 25,000 volts, the speaker has been investigating this matter lately and has obtained within the last two weeks from a number of the largest cable manufacturers, prices on high-tension cables for 11,000-volt, 25,000-volt, 35,000-volt and 50,000-volt service, having conductors of No. 0000 B. & S. gauge; also, not so recently, quotation on 75,000-volt cable of 50 square mm. conductivity. The 50,000- and 75,000-volt cables are single-conductor; all the other cables are three conductor, each separately insulated, laid up under one insulating jacket and covered with lead sheathing ⅛ in. in thickness and containing 3 per cent tin. The thickness of the insulation varies slightly with the different manufacturers, the specification calling simply for time-tests of double normal voltage. The curves shown represent present-day average prices for the different cables indicated. The curves were obtained by plotting the prices quoted for the several characters of insulation



at the voltages named and drawing lines, to represent the average, through the points as plotted. The speaker assumes it is fair to conclude that curves obtained in this way correctly indicate the cost of cables at any voltage throughout their length. The price indicated for three 50,000-volt paper insulated single-conductor cables is the average price; that for graded similar cables is the quotation of a single maker; the same with regard to the 75,000-volt cable, except that the cross-section is of 50 square mm. instead of No. 0000.

Where No. 0000 conductors are intended for 50,000-volt service or above, the thickness of the insulation becomes so great with three-conductor cable that it is impossible to put the completed cable through the leading machines at present available. It may be possible to develop machines of larger cross-section, but I believe at present about 3 in. is the largest cable that can be lead sheathed. This means that for the higher voltages requiring thicker insulation, single-conductor cables must be used which means increased cost compared with three-conductor cables. This is to the disadvantage of the higher voltages, but is compensated for by the fact that fewer spare cables are required as a reserve.

The conclusion that the speaker comes to from a consideration of these curves is that 25,000 volts is not the commercial limit for underground cables. There is no reason why the same commercial advantages cannot be obtained by increasing the potential to 35,000 or 40,000 volts, where the type of cables are three-conductor, because the cost increases in the same ratio as the potential both above and below 25,000 volts. Similarly, for certain conditions it will be commercially advantageous to use 50,000 or even 75,000-volt cables.

**John W. Lieb, Jr.:** I would like to say a word or two on the contribution made by Mr. Merz. As several of the speakers have said, the local conditions in this country are so different from those that prevail abroad, that it is very difficult, without giving them most careful consideration, to determine which is the better type of construction to use.

My own experience with underground construction abroad dates from 1882. In that year quite an extensive underground system was laid in Milan, Italy, using Edison tubes. It took just about six months in that particular locality to destroy a wrought-iron tube laid underground. The accumulated detritus of many centuries, together with the poor drainage and sewerage system, made these tubes subject to corrosion to such an extent that it showed conclusively that the Edison tube system which was in successful practical use in this country was not adapted to the new conditions, and as a result after 1885, steel-banded, lead-covered cables were used exclusively.

A few years later there was laid in that city one of the first 2,000-volt alternating current underground systems, using concentric cables. This type of cable, lead covered with steel band armor, has given splendid results abroad and is the type most extensively used.

The type of cable advocated by Mr. Merz is very much better suited to European conditions than our American drawing-in system, as they have to deal largely with built-up communities where they can more easily and readily foresee the probable future requirements.

**Philip Torchio:** Seven years ago Dr. Steinmetz gave us the mathematical theory of surges on high-tension systems. Since then the oscillograph applied to high-tension cable systems has confirmed graphically the values deduced from formulas and the numerical values of line and power constants, making the results of these investigations of great benefit to the operating and designing engineer alike. It is interesting to compare these oscillograph records with similar data obtained a few years ago by David on a considerably smaller system in the south of France and by Patchell in London. Messrs. Junkersfeld and Schweitzer have also experimented on a 20,000-volt line, which is double the voltage previously experimented upon. Their conclusion, that 20,000-volt cables do not act differently from lines at lower voltages, is not only valuable for its industrial application but also for the practical confirmation of the theories that have been advanced and their applicability to wider limits. For this the Institute is greatly indebted to the authors.

As a contribution to the experimental data of this paper the writer wishes to present a record of disturbances in the high-tension cable system of The New York Edison Company during the last few months. The history of all cable disturbances of this company for the first five and nine years was presented to the Institute by the writer in June 1903 and October 1907 respectively.

These two communications described the two types of instruments to give immediate indication of every "high-tension ground" on the cables or system. The first is an electrostatic ground indicator with suitable contacts and alarm bells, and gives indications of low resistance grounds only. The other is a selective ground indicator and indicates the lowering of insulation in advance of a dead ground, and also designates on which particular feeder (averaging 80 or 90) the ground is developing or has developed. Reference in the table is made to each type of instrument respectively by the designation, "electrostatic ground detector," and, "selective ground indicator."

From the theoretical point of view the above records are interesting in showing the existence of the time-element in the breakdown of insulation, the effects of momentary grounds on the system, etc.

This record, as well as the previous ones reported, includes abnormalities of all kinds however unimportant or inconsequential they may have been from an operative standpoint or in their effects on the system as a whole. A large proportion of the so-called "disturbances" or "defects" referred to were not on the Edison system at all but were located on the premises of large customers, to whom high-tension current was supplied.

As illustrating the value of these selective ground indicators from an operating standpoint, it may be of interest to cite one case of cable breakdown which occurred in January 1907, before the selective ground indicators were installed. One phase of a cable grounded and some sixty odd feeders had to be taken out of service, one at a time, before the grounded cable was

## TABLE I

Records of the operation of the electrostatic ground detector and selective ground indicator from June 1 to October 6, 1908

| Date, 1908 | Cause of indications | Location of defect | Time elapsed after location of defect by selective indicator before electrostatic ground detector operated | No. of drops down on selective ground indicator at first shock* | Remarks |
|---|---|---|---|---|---|
| June 10 | Short-circuit made by construction dept. | In sub-station | 0 | 1 | Cleared by automatic opening of feeder switches. |
| " 24 | Burn-out of motor coil | " " | 0 | 1 | Cleared by sub-station operator. |
| " 25 | Switch accidentally grounded | " " | 0 | 1 | Cleared by sub-station operator. |
| " 26 | Ground and short-circuit on 2 high tension feeders | In subway | 0 | 2 | Simultaneous ground on opposite phases of 2 high tension feeders caused short circuit which was cleared by the automatic opening of feeder switches about 2 sec. after its indication. |
| " 26 | Short circuit on high tension feeder | In sub-station | Electrostatic did not operate. | 1 | Feeder switch opened at same instant ground was indicated. |
| Aug. 1 | Ground on cable | " " | 0 | 1 | Cleared by sub-station operator. |
| 19 | Ground on one phase of high tension feeder | In subway | 10 to 15 sec. | 2 | Feeder taken out of service by system operator. |
| " 28 | Burn-out of 75 kw. lighting transformers | In sub-station | 0 | 4 | Cleared by sub-station operator. |
| Sept. 2 | 75 kw. lighting transformers grounded | " " | 7 hr. 40 min. | 2 | Instantaneous grounds occurring at 2 a.m., 7 a.m., 3:30 a.m., 4:30 a.m., 5:50 a.m., 9:36 a.m., 10:12 a.m., 10:39 a.m. Finally cleared by cutting out lighting transformer. |
| " 19 | Burn-out of 400 kw. transformer | " " | 10 sec. | 1 | Cleared by automatic opening of feeder switches. |
| Oct. 2 | Ground on one phase of high tension feeder | In subway | 3 to 4 sec. | 5 | Feeder taken out of service by system operator. |
| " 4 | Ground on lighting transformer | In sub-station | 0 | 2 | Instantaneous grounds occurring at 2:45 p.m., 5:05 p.m., and 6 p.m. Finally cleared by cutting out lighting transformer. |

In all the above cases both the electrostatic ground detector and the selective ground indicator operated.

* In all cases where more than one drop fell at the first shock the drop on all clear feeders stayed in after being once restored.

located. Two hours elapsed from the time the ground occurred before the faulty cable was located.

Attention is called to the fact that in five out of twelve of the cases reported the selective ground indicator gave its indications long enough in advance to enable the operator to clear the defect before actual short-circuit occurred.

The practice of the New York Edison Company in subjecting cables to high-potential tests differs somewhat from that given in the paper, in that new, altered, or repaired cable is subjected to a test of double working voltage between conductors and ground for 2 minutes, and 20 per cent above working voltage between conductors for 3 minutes.

**Chas. P. Steinmetz:** Electrical engineers are indebted to the authors for demonstrating that underground cable systems of magnitude and power can be operated with very few cable breakdowns, and, further, in such a way that the cable breakdowns do not involve the interruption of the system, but can be taken care of perfectly by the protective devices. This is the more reassuring when we realize that the destructive possibilities vary in almost direct proportion with the power back of the system. Underground cables have been operated for many years on arc circuits on 5000 or 10,000 volts with very little trouble. But these systems were of limited power. A cable of the same size operating under the same voltage may give satisfactory results on one system; on another results may be unsatisfactory, due to the greater power back of it.

It would be interesting to investigate still further how much stored energy there is available in this system, not merely the rated capacity of the engines and generators, but the energy stored in the magnetic field of the conductors, in the electrostatic field, and in the mechanical momentum of the synchronous apparatus, generators as well as synchronous motors and converters. All this apparatus is ready without a moment's notice to feed back their energy into any part of the system. It would be interesting, too, to calculate the maximum discharge rate of this stored energy, because it would be found that this apparently enormous power of 118,000 kw. is insignificant compared with the maximum possible discharge rate, which probably runs into the millions of kilowatts. This must be taken into consideration in discussing the action and operation of a cable system.

Theoretical investigation as usually found in the literature of this subject, shows that the maximum possible voltage cannot exceed double voltage. Here the spark-gap records much more. This shows that much of our so-called information on transient phenomena does not agree with the actual facts; that our knowledge is still incomplete. I believe that this subject is just passing from a chaotic state into a state where we shall begin to know something of value. Ten or fifteen years ago our theoretical ideas of the operation of transformers and generators did not agree with the performance of these apparatus. The same condition exists now with these transient phenomena. The phantom circuit of distributed capacity and inductance with which most of the literature deals, is a uniform circuit of uniformly distributed capacity and inductance, which oscillates with a definite frequency. Is it very different from the circuit existing in practice, which is a combination of circuits of different constants joined to the massed inductance of generators, transformers, etc., and in these complex circuits the voltage rise may greatly exceed double value.

I think that this investigation could be extended still further by inserting spark-gaps across sections of the circuit, across inductive devices inserted in series in the circuit, as current transformers. A short spark-gap, with a tell-tale paper, connected across the current transformer at the terminal stations and middle stations of the high-voltage system would give an indication of the direction in which the disturbance passed, and how far it extended. Furthermore it would be important if one could get an indication not only of the voltage, but also of the frequency of these disturbances, and of the volume of the high frequency oscillation of these transient phenomena. I believe that this can be done by combining a condenser with the spark-gap. If across the circuit a Leyden jar is connected in series with an air inductance, and the spark-gap is shunted across the inductance, such a system takes a current and produces a voltage across the spark-gap depending on the frequency and voltage. As the plain spark-gap gives us the voltage, the combination of the condenser gap and ordinary gap would give an indication of the frequency; and as the volume of the discharge through such a condenser circuit depends on frequency and voltage, a fuse in series with the condenser circuit would give an indication of the volume of the high frequency oscillation.

I do not think that the burning off of the needle points in the ordinary spark-gap is a satisfactory indication of the volume of the oscillation, because the current following the discharge is also the normal machine current. The result depends to a considerable extent on the point of the generator wave, but a spark-gap and a condenser in series would exclude the machine current. The practical importance of the investigation of frequency is that perhaps the destructive effect of such a high voltage depends very largely on the frequency In such a cable system the high voltages may be fairly moderate in their frequency, perhaps not more than a few thousand cycles at the highest, or they may be of extremely high frequency, many hundred thousands of cycles. In the latter case they would be local, and even at considerably more than double voltage they would be practically harmless; with low frequency they may extend over a very considerable part of the system and be most destructive.

The greatest assistance in studying what may occur in the circuit is afforded by the oscillograph. This instrument bears the same relation to the electric circuit that the indicator does to steam engine practice. The oscillograph should enable the electrical engineer to determine all that takes place in the electric circuit; he should be able by means of it to recognize a danger signal, and know when the disturbance is harmless. That is, he must become familiar with the meaning of the different wave shapes.

In the oscillograms of the current there are quite a number of shapes. For instance, in Fig. 7 there is the characteristic effect of the hysteresis cycle of the transformer. In Fig. 5 there is shown the effect of the line intensifying higher harmonics. In this particular case it is the fifth harmonic. It is gratifying to see in all these oscillograms that there is nothing to indicate any dangerous condition in the circuit except the voltages at 7 and 8 in the two curves in Fig. 6. They look suspicious, and should be further investigated.

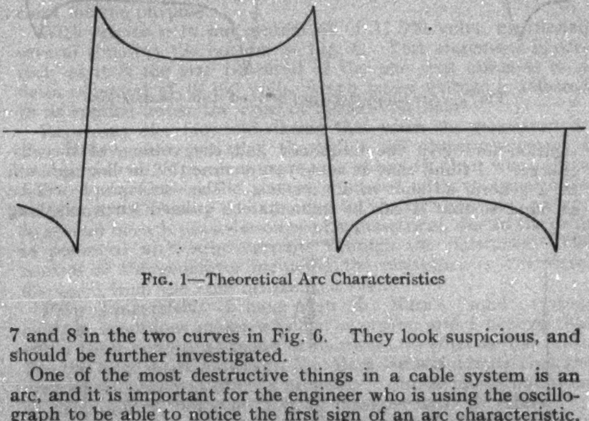


FIG. 1—Theoretical Arc Characteristics

One of the most destructive things in a cable system is an arc, and it is important for the engineer who is using the oscillograph to be able to notice the first sign of an arc characteristic. This characteristic is in most cases very definite, it is a double peak of voltage, a characteristic double peak. Occasionally there are double peaks in generator waves, especially in three-phase machines between the neutral and the line. In that case there is no danger, but when a curve like that in Fig. 1 is shown, then there is something in the system in the form of an arc, which is likely to produce destructive voltages. The characteristic is a rapid rise and rapid dropping off, to two sharp peaks separated by a wide valley. The first peak is frequently far higher and the second one may almost disappear, as in Fig. 2. Even the magnitude of the danger of producing destructive voltages by the arc can be recognized from the curve, by the pointedness of the peaks, and occasionally in the extreme case one sees the first peak resolved into a local oscillation, and the valley then more flattened out, as in Fig. 3.

I hope that the authors will extend the scope of their investigation and give the frequency and the volume of the discharges. I think that at some future time the oscillograph will be a general adjunct in all systems. The oscillograph will be at hand so that it can be immediately utilized when anything goes wrong—a generator runs away, a machine burns up, or a short-circuit occurs. If these records could be taken at the time they would be extremely important in helping us to avoid these disturbances.

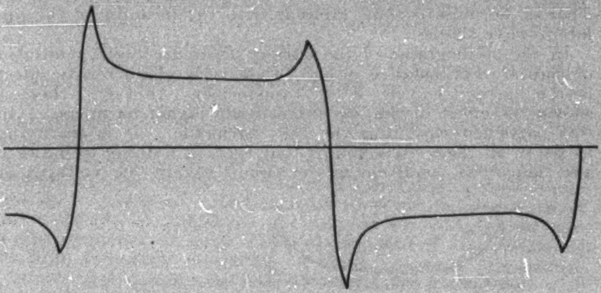


Fig. 2—Arc Characteristics derived from Oscillograms

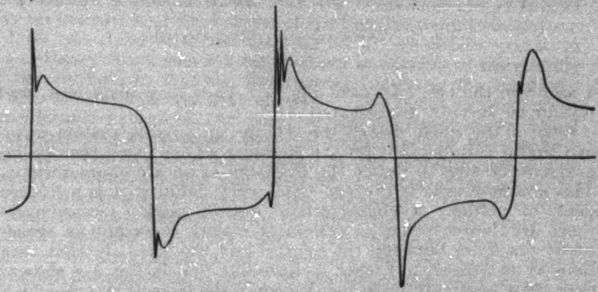


Fig. 3—Arc Characteristics derived from Oscillograms

**E. O. Schweitzer:** In answer to Mr. Fisher's query regarding the meaning of " double-working voltage: " this means double the normal voltage between phases, and between phases and ground; that is, if the normal operating voltage is 19,100 volts between phases and 11,000 volts between phases and ground, the test voltage is 38,200 volts between phases and 22,000 volts between phases and ground.

With reference to Mr. Fisher's suggestion that two and a half times the normal operating voltage be used in making potential tests on new lines on account of the fact that our spark-gaps showed potentials of 25,000 volts for a line operating normally at 19,100 volts between phases and 11,000 volts between phases and ground. We do not consider this advisable, as this double voltage test is applied for a period of one minute, whereas the surge potential lasts for but a small fraction of a second. The strain on the insulation being a function of both the voltage and time, we, therefore, consider this double voltage test sufficient for the purpose.

With reference to our statement of 11,000 volts, mentioned several times at the bottom of Fig. 4. This statement is correct, as it is the star potential of the line that operates at a delta potential of 19,100 volts, which latter voltage is referred to as coming under the class of 20,000-volt lines.

Regarding the footnote stating that when the generators at Fisk Street were grounded through a 2.6 ohms resistance, a voltage rise of 30 per cent more was obtained, than when there was one machine on the system grounded without appreciable resistance. This may be explained by the fact that the voltage to ground of each phase becomes unsymmetrical, due to the drop in potential with large currents through the resistance. The neutral of the generator including the resistance is, therefore, displaced from the true neutral position.

**Peter Junkersfeld:** I have seen Mr. Merz's "solid" system and the conditions under which it operates, and I believe that under those conditions many of us would do what he has done. For the large cities, however, Mr. Merz himself admits that the drawing-in system is often a necessity. Under most conditions in this country, however, I must disagree with Mr. Merz.

As to Mr. Fisher's comment, I will answer that the insulation of the 20,000-volt 00 cable is $\frac{9}{32}$ in. wall over each conductor, and $\frac{6}{32}$ in. wall over the three and is of paper. The cable is installed mainly in 3.5 in. duct, with square holes, although some two or three miles is installed in a duct that has 3-in. circular openings. The cable is a trifle large for a 3-in. duct, and is intended for a 3.5 in. square duct.

I agree with Mr. Fisher that workmanship is very essential on the joints, but there must be not only good workmanship, but also good compound, and good methods to insure good results.

Our experience with paraffin has not been satisfactory. In making joints it is, of course, absolutely necessary to exclude air, and as is stated in the paper, the joints are filled with a high-grade compound, and this compound, very hot, is poured slowly so that the probability of any air or voids is reduced to a minimum.

Mr. Stott and others have mentioned the increasing danger when the generating capacity becomes so great. In our system the rated capacity of the three stations connected to the system is 100,000 kw. for the Fisk Street station at this time, 28,000 kw. for the Quarry Street station, and 18,000 kw. for the Harrison Street station, making a total of 146,000 kw. We operate the system in two sections, but even with this precaution the possible amount of power that can be delivered instantaneously from either of the two sections is very large indeed because of the instantaneous short-circuit current of the turbine-driven alternators.

Mr. Clark made some reference to the breaking down of the cable to ground. That has been our experience for several years. If the cable must break down at all, we would rather have it break down to ground first. The neutral is grounded, and we use three single-pole relays. The usual experience is, if one of the conductors goes to ground, that at least one of the other two conductors remains continuous and a test can then be made quickly and the fault located in a short time.

Regarding the comparison between the insulation of the 9000 and the 20,000-volt cables. That is largely a matter of local conditions. The 20,000-volt cable has not as large a factor of safety but it does not need it. The 9000-volt cable does, as it supplies a district in the central part of the city.

Regarding Mr. Floy's statement of higher voltage cables, I do not want to dispute the figures he has given, but cables for 35,000 or 50,000 volts will require special duct or other construction. I think that it will probably be some time yet before we see any very extensive 35,000 or 50,000-volt underground systems. It is difficult to justify them commercially, even if they could be installed and possibly operated with reasonable success.

**Ralph D. Mershon** (by letter): The authors suggest that, as transmission voltages increase there may be instances where it will be advantageous to build transmission lines after the manner of protected bus-bar construction. This suggestion is rather an interesting one. It is especially interesting to me, because about two years ago I made some estimates on the cost of building a transmission somewhat along the lines I understand the paper to suggest. It occurred to me that if we should build a transmission line with comparatively short spans and with supporting structures just high enough so that there would be no chance of an arc between the lowest point of the line cable and ground, and then build along and over the whole line a casing or continuous house of wire netting, the cost might not be prohibitive, and a number of advantages would result, amongst them being immunity from lightning troubles and ease of repair. An estimate was made with reference to a rough design I prepared in which the line cables were to be about 6 ft. from the ground at their lowest point; the height of supporting structure and length of span being such as would, for this clearance, result in the greatest economy. The idea of the wire netting resolved itself into a high fence of this material, on each side of the line, and for the wire netting roof were substituted a number of grounded cables, supported upon the line structures parallel to the line wires and over them. These grounded cables were to serve the double purpose of protection against lightning and protection against baling wire and similar troubles. The cost of this design was compared with that of a tower line of the same capacity and, while the former was somewhat the greater, the difference in cost was not such as would be prohibitive where large amounts of power are to be transmitted.

If such a construction were used, it would be necessary at road crossings, either to go overhead on high structures or underneath through tunnels. The former could be carried out without great difficulty, maintaining practically the same construction on the higher supports as that used near the ground; or the latter could be adopted where the contour of the ground rendered it possible to take care of the matter of drainage.

I should not be surprised if, in time, some such construction as that suggested were resorted to for transmission lines carrying very high voltages, especially as it seems to me not unlikely that as voltages go higher, the insulator will develop to a form and a size comparable with that of a transmission line pole. With the construction suggested, then, the three-line conductors will be best carried upon three separate lines of poles, each pole being, for the major portion of its length, an insulator.

Of course, instead of the grounded cables and the wire fences, we might substitute sides and a roof of corrugated iron which would not only afford the protection previously mentioned, but also protection against the weather, rendering the insulation problem less expensive. In such case, however, the damage resulting from an arc to ground or between the line cables would probably be more serious than in the construction above proposed.

**H. W. Peck** (by letter): About one and a half years ago suspicion was aroused that there were high-tension surges on a 13,200-volt underground transmission system in Baltimore, and oscillograms were taken under various conditions to determine the actual presence and causes of the surges. The system, at that time, comprised four 2000-kw., 13,200-volt star-wound generators commonly run with the neutral of one machine grounded through an iron-grid resistance; about 24 miles of 0000 three-conductor, paper insulated, lead-covered cables; four 13,000-volt, synchronous motors driving 60-cycle generators and a number of step-down transformers, supplying synchronous converters. The oscillograms were taken at one sub-station located about 4 miles from the generating station. No rise of potential was discovered at the time of synchronizing an additional generator at the power house or a 1000-kw. synchronous motor at the sub-station, nor at the time of taking off either of these machines. The only condition observed which did give a rise in potential was the connecting of the dead line to the system or to a single generator with which we were testing. With the neutral of the test generator not grounded we obtained a rise in potential of 180 per cent of the normal. With the neutral of the generator grounded through heavy copper wire we obtained rises of potential of 150 per cent, 300 per cent, and 400 per cent of normal.

Further investigations were made with the oscillograph of the overhead distribution and in so doing one observation resulted which is perhaps of value in connection with such investigations. While adjusting for a certain test and observing the form of curve by looking at the image on the ground glass and shaking the head at right angles to the motion of the light there was observed a very irregular wave form. Investigation disclosed no apparent cause for this irregularity and repeated attempts were made to duplicate the same with the film, resulting finally in getting something very similar to that which had been observed. This suggested the value of throwing a reflection of the oscillogram by means of a vibrating mirror upon a screen and observing the reflection for a long period of time, noting whether irregularities did exist and if so endeavoring to ascertain any peculiar conditions obtaining at that time.

## DISCUSSION ON "HIGH-POTENTIAL UNDERGROUND TRANSMISSION." BOSTON SECTION, NOVEMBER 18 1908

**A. E. Kennelly:** This whole subject is one of great importance, because cities are growing and more wires have to be installed, while wires already in existence have to be put under ground. The underground construction involves great expense, and the questions of the construction, preservation, and operation of these cables are of immense importance from every standpoint. The subject is full of interest.

**N. J. Neall:** I should like to ask Mr. Elden what proportion of the total disturbances to the Boston Edison distribution system from all causes is created by cable failures and what is their nature.

**L. L. Elden:** Our records go back for only two years. The failures in the transmission system are the smallest item in the way of disturbances that we have. Our overhead systems give us considerably more trouble than our cable systems, and I may say that such cable troubles in the transmission systems as have happened during the years 1907 and 1908 have almost entirely resulted from cable newly installed. In six of the cases the cable was clearly defective and was replaced by the manufacturer. In the remaining two cases recorded the troubles were due to mechanical injuries to the cable, for which the manufacturers could not be held responsible.

One of the most serious features resulting from cable breakdowns is the interruption of a considerable capacity, which at times of maximum load is usually supplied over each individual cable.

The normal maximum operating capacity of the standard 0000 three-conductor cable at 6600 volts for peak-load purposes is 2500 kw. In order to prevent the interruption of this capacity from interfering with the service, it is customary to install two or more transmission lines to each sub-station, these lines being operated at all times individually at the sub-station ends, each carrying a part of the station load. Under these conditions the duplicate line is always ready for use, and in case of trouble the operator may quickly transfer to the spare line without any appreciable disturbance to the system in the direct-current districts and only a momentary disturbance in the alternating-current districts.

One very serious factor has to be dealt with by all companies operating cable systems in cities where the return currents of railway systems are present. This is true with us, although a very careful watch is kept on all districts so affected.

**M. V. Ayres:** The company with which I am associated has about 2.25 miles of three-phase, lead-covered cable in three sections hung up on poles like telephone cable. This is a 25-cycle, three-phase, 13,200-volt transmission. The cable is paper-insulated and lead-covered. One of these lengths of cable has been up since the spring of 1903. The others were put up not long afterward. We have very little trouble with them. Most of the troubles have been due to the fact that they have been hung on poles and run through trees, and are therefore subject to various kinds of accidental injury. We have had hardly any trouble that could be laid to the cable, the splices, the end-bells, or anything of that kind. We had one breakdown in a splice during a lightning storm which I think was due to poor workmanship. The latest trouble with that cable is typical of the kind of trouble we have. A trolley wire broke and pulled over in such a way that it charged the iron bracket supporting the trolley wire, and the current leaked to the cable sheath. Of course the cable sheath was grounded. Enough current passed not only to burn a piece out of the lead cover, but to set fire to the pole. The fire continued for fully 15 min. before the cable broke down. I arrived while this burning was going on, but could do nothing to stop it. I called up the power house ; they had not noticed any trouble then, but did shortly afterward.

This brings to mind the fact that I have been amazed by the number of minor injuries that can happen to that cable without resulting in transmission trouble. We have had holes burned in that cable many times without any serious results. Our practice has been, when we have found a hole to make a temporary patch on it, with tape, and then at the earliest opportunity make a wipe of lead over it. After that there is no further trouble. Some of these holes have existed a long time without resulting in any transmission line trouble. I have faith in the excellence of paper-insulated cable in all ordinary transmission work, although I have had no experience with underground work of that kind.

**G. W. Palmer, Jr.:** The Old Colony Street Railway Company has had some very gratifying experiences in connection with the maintenance of high-tension transmission cables underground. They have had operating in a quiet way for the last 5 years some 15 or 16 miles of 13,200-volt cables through which is transmitted almost all the current necessary to feed the entire Old Colony system. This system covers the greater part of eastern Massachusetts except Boston, and in some cases the energy is transmitted 50 or 60 miles from the main station. Since the cable was installed there has not been a single instance of disturbance of operation from any trouble. In fact the cable part of the system has shown itself to be the most reliable of any, more reliable than the overhead line of the sub-station or the main station equipment. About a year after a certain section was put in a joint blew out. It did so without making any disturbance which could be noted at the main station or substations, and the occurrence was not known until the manhole was visited; although the conductor was bared, the cable was still operating at 13,200 volts. I think the cause of our good fortune with the cable installation has been the extremely high class of insulation used and the care with which the cable was put in. The cable was built to stand a factory test of 40,000 volts after installation, although that test never was applied to it.

**N. J. Neall:** In the work that I have been called upon to do at various times cable design and operation come into very close connection with lightning protection apparatus. I remember a case which came up some time ago on a newly installed line consisting of approximately 1.5 miles of 25,000-volt cable. It was necessary to go through a city underground. It had not been in operation very long before the lightning season began, and in this particular locality lightning was rather frequent and severe. The cable began to break down periodically almost in synchronism with the lightning storms. The manager, who was very anxious about the continuity of his service, called upon the cable manufacturer immediately to explain why he had those troubles. The cable manufacturer claimed it was the fault of the lightning-arresters; while the arrester man wanted to say that the cable man was at fault, he only said there was a reasonable doubt. As a result the operator was asked to provide a full system of inspection of the lightning protection by means of tell-tale papers and by special spark-gaps placed at various parts of the cable system.

I am sorry I do not know the result of these observations. I do know, however, that the system was much improved, but I have half a suspicion that it was largely for the reason brought out to-night—that the cable became seasoned, and that all these joints were finally brought up to concert pitch. I doubt very much whether static troubles were to blame, save in the first case. I mention this incident merely to show that it is desirable to have some definite information on these points, and that it is absolutely impossible to refute the statements of the cable manufacturers when defending something weak in connection with the cable joints, unless there is so aggravated a case of bad workmanship that the trouble can be found right there. I do not want it understood that I think lightning protective apparatus is perfected; there is much yet to be hoped for.

It has been the practice that all cable shall be tested at certain over-potential; I make it a point to protest against this requirement, because I do not think it is instrumental in bringing out entirely the quality of the cable. My experience has been that a breakdown usually occurs after a ground, or more often after a short-circuit on some part of the system, perhaps external to the cable system, particularly if it be connected to an overhead transmission system. I think, therefore, that any such overcharge test on the cable itself is likely to impair it needlessly; that it does not indicate its ability to combat the sudden strains just mentioned.

The chances are that with the present state of manufacture, the quality and dielectric strength of the cable can be reasonably determined without subjecting it to this high strain. A very good test of the strength of the disturbance might possibly be obtained by an equivalent spark-gap measurement. A standard length could be subjected to static discharges, and the opening of a gap in shunt to the cable that would just take these discharges could be noted. This would give some measure of ability to absorb or to pass those operating disturbances which have all the characteristics of high frequency in their initial effect. I have never made any experiments on cables under these conditions, but it appears to me that the method could be adopted to give some guide to the behavior of the cable under those circumstances where there are "rushes" and not steady rises of potential to deal with.

**Dugald C. Jackson:** It is the ambition of the Commonwealth company, as I understand it, to put itself in a position so that there will be no extensive generation of primary power in Chicago except that carried on in its own stations. The realization of such an ambition would be of real advantage to the city and its people, and has been so recognized by the city council. The Chicago city council has therefore taken the ground that small franchises for the electrical generation and distribution of power shall not be hereafter granted, and that such existing franchises should be extinguished as far as possible. The idea seems to be that every small station is a disadvantage to the city because it fouls the atmosphere, and it serves part of the best and most profitable territory at competitive rates and thus forces the larger company into a position where it cannot reduce its rates to a satisfactory low average for the entire territory of the city. Many small electric plants usually exist in the large cities, plants furnishing energy to one or two large office buildings and the like. The people operating such plants become ambitious and perhaps endeavor to obtain a franchise to cross the street. That means supplying another block. Ultimately that may develop into a four-block plant. Franchises of this kind are being refused in Chicago for the reasons already stated. The Commonwealth company has been required, however, to put its rates at figures which are thought to be reasonable, accompanied by a sliding scale of reduction for a certain period of years.

The Commonwealth company has already gone so far in its ambition to become the great primary power purveyor for all uses in the city, I understand, as to make a bid for the generation of power for drawing all the trunk-line railroad trains into and out of the city of Chicago which the railroad managers arrange to handle by electric power. This is quite a large project. Whether the Commonwealth company will succeed in persuading the great railroad interests that it is to their advantage to buy power is yet to be seen, as none of the large railroads has yet undertaken to draw trains into Chicago by electric power. That the the intention of the Commonwealth company is likely to succeed is indicated by the fact that the company is already supplying much power to electric street and elevated railways in Chicago.

The great stations that are to-day operating in Chicago, Boston, and other cities, were virtually out of the question under the old basis of reciprocating-engine generation, but the ease of operation is apparently as great with a 50,000-kw. steam-turbine station as it was with a reciprocating-engine station of not exceeding 12,000 or 15,000 kw. capacity. A few years ago it was thought that 5,000 kw. was near the limit of construction for a generating unit. Now 5000-kw. turbines are commonplace. If something very much larger than we have now in the way of generating units and generating stations does not materialize, the ambitions of the Chicago company will result in half a dozen stations; with 30,000-kw. units, however, perhaps the Chicago company could do the work they attempt to do with two or three stations.

A second factor which is brought out in this paper is the lack of analytical knowledge in regard to dielectrics and insulations. Although we may know the dimensions and kinds of the materials of which a cable is manufactured, we cannot compute with certainty its electrostatic capacity. The computations made are largely by rule-of-thumb. In other words, the science of cable construction lags behind the science of generator construction. By generator construction I mean the entire system beginning with the device that consumes the coal and ending with the device that delivers the electric power to the transmission lines.

Insulation is to-day truly one of the great problems of the electrical arts. We need an answer to the question: what causes dielectric properties, and why are some materials insulators and others conductors? Not until we begin to approach the answers are we likely to have that analytical knowledge of the electric transmission of power which is needed to make electric power of universal service.

The oscillograph has clearly been serviceable in the Commonwealth power house. I have thought for some years that the oscillograph might be of pretty nearly as much value to the transmission man as is the wattmeter. It has not been many years since the power transmission man thought that a wattmeter was a supernumerary. He went by ammeter or voltmeter, but he finally found it necessary to follow the dictates of analysis and take to the wattmeter and its indications. He now looks upon the oscillograph as a supernumerary, but the oscillograph in certain forms is coming to be an instrument of commerce as well as of research.

**L. L. Elden:** I would like to refer for a moment to Professor Jackson's remarks on the Commonwealth system of Chicago. Those who are not operating these large cable systems, I think have no realization of what happens at the generating station when a defective cable develops in a location in close proximity to the station. Upon the occasion of a recent burn-out of a turbine in one of the Chicago stations when operating with a very large generating capacity, the cables forming the generator leads between the generator and the switchboard were not only punctured, but were so seriously affected mechanically that the conduit containing the cables was also badly damaged. From this, one may judge what problems are to be met in cable construction in the future if the large stations continue their present rapid rate of growth; the result will probably be the division of the generating stations into sections in order to reduce the capacity concentrated on one bus-bar. This is being done in Chicago at the present time.

The New York Edison Company operates the largest generating capacity in the world on a single bus-bar, the peak load last year being in excess of 120,000 kw. The concentration of this capacity in a short-circuit within or adjacent to the station produces conditions very difficult to control; it is probable, therefore, that in future means will have to be provided to limit the amount of current that can be concentrated in a fault.

This company has in service a device invented by one of their engineers which has been described in one of the papers presented to the Institute. This device performs the duty of detecting breakdowns or defects in individual cables a sufficient time in advance of an actual short-circuit to permit the disconnecting of the defective cable from the system before serious trouble occurs. The actual record of the use of this device on their lines indicates a successful application to practice, as in answer to recent inquiries it was stated by the engineers that with the exception of four cases to date, the indication of trouble on cables had been given sufficiently in advance to permit of the disconnecting of the defective cable before it actually broke down. It would seem then that further perfected apparatus would prove of great value to all companies operating large cable systems.

Professor Jackson referred to the rapid development of the systems of the large companies. I recall that 10 years ago this month the Boston Electric Light Company built their station at L Street and planned for six 1500-kw. generators. At the rate of development in progress at that time it was believed that sufficient capacity was being provided for a long period in advance, yet within 3 years it was necessary to add two more units equivalent to 50 per cent of the original installation. Contrasting this with the present conditions, it is interesting to note that the Boston Edison Company is now regularly installing individual units cach of a greater capacity than six of the original 1500 kw. generators above referred to.

Referring to high-tension cable tests, I do not know that our experience quite agrees with that of the Old Colony system. Our experience indicates that the method usually employed of connecting the cable to the system without tests almost always results in some disturbances or troubles before the cable gets down to a working basis; and while the experience of other companies who make high-potential tests shows that they practically clear their cables of these troubles before they are actually placed in service on the system, there is a considerable difference in the practice of the large companies in making high-potential tests. Some arrange to apply 30-min. tests at double working pressure after the cable has been installed, while other companies reduce both the time of application and the limit of pressure applied in their individual practice. It is generally the practice to omit tests of double working pressure after the initial test of the cable at installation, all further tests being confined to pressures slightly in excess of the regular working pressure of the cable, such tests being made only after a cable has been repaired, due to the development of poor insulation or in actual breakdown.

Several different types of apparatus are used for the purpose of making these tests, two of the most common being a motor-generator or a static transformer. The Chicago company uses a motor-generator arranged for operation at variable voltage, their practice being to raise the voltage on a cable under test very gradually until they have reached the limit which their experience indicates as satisfactory. After applying the test for such time as they deem necessary, the cable is then connected directly to the main system. In but one or two cases have faults developed after such tests have been made.

The New York Edison Company uses static transformers for similar purposes, arranged for the gradual application of the test voltage to the cables in practically the same way as that done by the Chicago Company with their motor-generator equipment.

The Boston Edison Company is at present contracting for a transformer testing set to accomplish the same purposes, which equipment will probably be installed during the coming year. The company is advised by the cable manufacturers that the duplication of such tests as above described will be perfectly satisfactory from their standpoint, except that there are some objections to the application of the double-potential test for anything except a very short period of time, after the initial test of 30 min. has been made when a cable is first installed.

In nine cases out of ten, we have had very satisfactory operation with our relays. We are using the bellows type relay, and I think our experience has been similar to that of other companies using this type of relay. Our experience indicates that frequent adjustments are absolutely necessary in order to keep the relay in adjustment, and such troubles as we have had where selective operation has been required have been found to be due to imperfect adjustment of the relays. Aside from these troubles, we have obtained very satisfactory operation, both on individual lines and on lines where selective operation has been necessary.

*A paper presented at a meeting of the Pittsburgh Section of the American Institute of Electrical Engineers, Pittsburgh Pa., November 10, 1908.*

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# ELECTRICITY IN MINES

### BY GEO. R. WOOD

Before describing some typical coal-mining plants, with their especial features, the author will outline the ordinary mine development and some of the standard electrical mining equipment.

Assuming that the coal vein lies almost horizontally, with an average dip of, say, 1.5 to 4 or 5 per cent, the main headings or tunnels are driven to the raise where possible, so that grades will favor the loads. At intervals of about 1200 ft., cross-headings or flats are driven at right angles to the mains, and from these, parallel to the mains, are driven room-headings or entries, from 300 to 600 ft. apart. The rooms or chambers from which most of the coal is taken are turned from these entries, and are started in about the same width—10 ft.—as the entries. When in about 20 ft. they are widened out to full width—from 20 to 30 ft. These rooms are driven on about 40-ft. centers, leaving a pillar of coal between them from 10 to 20 ft. thick, to support the roof.

The thickness of coal in the Pittsburgh seam runs from 5 to 7 ft., in the Connellsville basin from 6 to 9 ft., and in central Pennsylvania from 3 to 5 ft. In a completely equipped electrical mine, the coal is undercut by electrical machines, hauled from rooms to cross-headings by small gathering locomotives, and from cross-headings to main tunnels and thence to the tipple by larger locomotives. Electric pumps of various sizes handle the water; electric motors drive the fans which ventilate the mines; and car-hauls, crushers, elevators, and the like, where used, are also driven by motors.

Electrical mine locomotives and machines have been in use for more than 20 years. Originally very crude and expensive to operate, they are now highly developed and satisfactory pieces of apparatus. Some of the first locomotives were made of street-car trucks weighted down. Many were of the single-motor type, with connecting rods or with chain drive. The motors were not enclosed, and the trolley was of the pantagraph type. For a long time the equipment was inadequate, largely on account of the narrow gauge as compared with street-railway work, and also because each locomotive was proportioned for particular service, which afterwards increased as the haul was extended. The equipment was based on about 5.5 h.p. per ton, which will stand an intermittent service fairly well, but is not sufficient for long hauls or on heavy grades where sand is used.

Modern locomotives have usually two series motors, with a total capacity of about 10 h.p. per ton of locomotive weight. These motors are rated at 75 degrees cent. rise in 1 hr., or in some cases are rated for 40-min. service. A rheostatic controller with grid resistance is used, and motors are operated in parallel on heavy pulls and in series for switching. The change is made by a four-point reversing cylinder. In a new controller for heavy work, each point on the controlling cylinder has a double-contact finger and a separate blow-out coil. Arc headlights are largely used.

In many mines it is desired to gather the wagons from rooms to cross-headings by motors. For this service small locomotives weighing from 4 to 6.5 tons are used, and since it is not desirable to have trolley wire in the rooms, these locomotives are provided with cable reels. These reels are arranged automatically to reel out cable when running into rooms, and reel it up again on coming out. The cable is hooked over the entry trolley and supplies current to the locomotives. The reel may be driven by a sprocket chain, through a friction clutch, from the axle of the locomotive or from the shaft of one motor. The reel may also be operated by a coiled spring, if the cable be not too long, or by a small series motor connected permanently in circuit. Where grades are very heavy against the load, a wire-rope reel, with a small independent motor, is sometimes provided. In this case, the locomotive remains at the top of the grade, lowers the empty car by gravity and hauls up the loaded wagon by the wire rope.

Main-line four-wheel locomotives are not often made heavier than 14 tons, on account of the heavy rail required. When more power is needed, six-wheel, three-motor locomotives are used, of from 15 to 20 tons weight, or two four-wheel locomotives are coupled together with a single four-motor controller, and with the brake rigging operated from one lever. These tandem locomotives are sometimes so arranged as to be easily disconnected and worked separately when desired.

Electric coal-cutters were first of the "cutter-bar" type, in which the "bits" or small chisels were staggered around the surface of a horizontal cylinder, which was rotated and forced under the coal, making an undercut of a width and height equal to the length and diameter, respectively, of the cylinder cutter head. The next type was the chain-breast machine, which is very largely in use at present. This type comprises a stationary rectangular frame and a moveable frame, carrying the motor, gearing and cutter head, travelling within the stationary frame. The cutter head is the base of a long isosceles triangle, around which the chain is driven by a sprocket at the apex. This chain carries a number of cutters or bits, about one-third being uppers, one-third lowers, and one-third centers. The chain is fed forward into and under the coal by a rack-and-pinion feed, the cut being about 4 or 5 in. high and 44 in. wide. Both types of machines, after making a cut to the desired depth, are shifted side-ways; the operation is repeated until the face of the room is undercut completely across, after which the coal is blasted down.

A new type of machine is an electrically driven puncher. This puncher consists of a vertical motor with gearing, and a cylinder and two pistons, one of which is driven by the motor, the other carrying the cutting-tool or pick. The rear piston, driven by the motor, compresses air on its backward stroke, and the front piston, carrying the tool, is forced back by atmospheric pressure. At a certain point the rear piston passes a port which admits the compressed air between the two pistons. As the front piston is free to move, it is driven forward, causing the tool to strike the coal with great force. Should the pick not strike the coal, the blow is absorbed by an air cushion at the front of the cylinder. This machine is mounted on a pair of wheels, like the air puncher, and is operated in substantially the same way.

Another type of under-cutting machine is similar to the chain-breast machine, except that after making the first undercut, instead of withdrawing, moving sideways, and repeating the forward cut, this machine remains under the coal and is drawn sideways across the room, cutting as it goes. This type is especially adapted for cutting wide rooms or long faces, and is called a "long-wall" machine.

Machines have also been designed to cut and load the coal, without blasting. One of these is made up of two discs or cutting wheels about 4 ft. in diameter carrying bits in the periphery, mounted side by side and rotated in opposite directions. These are fed into the coal and undercut it, carrying the cuttings to the center, where a conveyor chain picks them up and feeds them back into a car. At the same time, two puncher machines, mounted above the wheels and one at each side, on swivels, are used to break down the coal as it is undercut, the cutter wheels throwing the coal to the center whence it is carried back by the conveyor. This machine as first designed is operated by compressed air.

Another machine has a double cutter head, like two standard chain machines, one above the other. The double head is swung in a vertical plane, describing an arc of about 180 degrees, like a steam shovel, except that the cutting is done on the down ward stroke. This machine cuts the entire vein into fine slack, which is preferable for coking.

Electric mine pumping does not differ essentially from power pumping on the surface, except that the water is usually acid, and that grit and fine coal must often be handled. In the geared-type plunger pumps, the valve lift is increased to allow the passage of fine coal, etc., and the cylinders, plungers, valve seats and stuffing boxes are made of acid-resisting material. In some extreme cases cement-lined pumps with wooden plungers are used, or the entire pump is wood-lined. Where the water is not too strongly acid, and other conditions are favorable, turbine pumps are used, eliminating valves, packing, gears, etc. Rotary pumps of new design are also coming into use where the water does not contain much grit.

One of the first electrical mining plants in the Pittsburg district was that at Grindstone, near Brownsville, Pa. The generator was a bipolar machine of about 60 kw., driven by a Corliss engine through a countershaft. It is still in daily operation. Cutter-bar mining machines were operated.

The two largest plants at that period were those at Essen, near Carnegie, and Scott Haven, above McKeesport, both of which are now operated by the Pittsburgh Coal Company. The Essen plant supplied two mines, and consisted of three bipolar, 250-volt, 150-kw. generators, belt-driven. A number of mining locomotives were used, these having but one motor, carried lengthwise in the locomotive frame, with bevel gears at each end. On account of this positive connection to all driven wheels, and also on account of the steel-tired wheels, these locomotives had a very high draw-bar pull, but they were expensive to operate on account of the difficulty of holding the bevel gearing in line.

The Scott Haven plant, installed in 1895, supplied four mines, and consisted of four belted, 550-volt, 100-kw., four-pole generators. The switchboard was a skeleton oak frame, with round copper bus-bars, the switches being front-connected. On account of the high potential, a metallic circuit was provided for the mining machines as being safer for the men, but this circuit quickly became grounded in the mines. All the apparatus was later put on a grounded circuit with rail return.

The locomotives in the Scott Haven plant were of the two-motor type and mechanically of modern design. The motors were of about 23-h.p. rating on 10-ton locomotives. The armatures were cross-connected and were very difficult to rewind. These motors were replaced in 1898 by 35-h.p. motors for narrow gauge use, originally designed, the author believes, for the Boston Elevated Railway. One of these locomotives has still in service the motor installed in 1898, the armature never having been taken out.

The installation at Scott Haven included some of the earliest motor-driven fans and pumps. Practically all of these are still in use.

One of the first direct-connected plants was installed in 1897 at Moon Run, about 5 miles West of McKees Rocks. This plant was first used for haulage alone, and included one 165-kw., 250-volt generator, driven at 240 rev. per min. by a center-crank engine. Another unit was installed later with a side-crank engine, but before this was in place the center-crank engine shaft broke in the disc. It was operated for several weeks after breaking in two, until the other unit could be started.

One of the first alternating-current central plants for coal-mining purposes was installed in 1902 at Gary, W. Va. This plant first contained two 400-kw., 6600-volt, 25-cycle generators, driven by twin simple engines with independent governors.

The exciting equipment consisted of one 25-kw. vertical engine-driven unit and one 25-kw. generator direct-driven by a 40-h.p. induction motor at 720 rev. per min. All oil switches were in brick cells back of the switchboard, with remote manual control, the feeder switches being of the automatic overload release type with time limit relay. The generator switches were non-automatic.

The longest transmission was originally 3 miles. Three substations were built, each containing one 150-kw., 275-volt converter with step-down transformers and the usual switchboard equipment. Each sub-station also contained step-down transformers for induction motors at tipples, etc. Direct current from the converters was used for haulage only, supplying main-line and gathering locomotives of the cable-reel type, and the larry equipments for the coke ovens. These larry equipments included one motor with a reversing controller, resistance and trolley, and the motors were duplicates of those on the smaller locomotives. Each larry could haul one trailer.

Induction motors are used on single-stage, two-stage, four stage and five-stage turbine pumps, for coke oven supply; on crushers in sizes of 75, 200, 300 and 400 h.p. at the tipples; on mine fans, for which purpose two-speed, changeable-pole, 100-h.p. and 150-h.p. motors are used; for driving deep-well pumps and small compressors for air lift, with silent-chain drive; and for driving picking tables, car hauls, conveyers, etc. at tipples.

This plant was later increased by adding two 750-kw., 6600-volt generators, driven by cross-compound Corliss engines at 125 rev. per min. At the same time the original twin simple engines on the smaller units were changed to cross-compound, giving better regulation and economy. Within the past year one 1000-kw. steam turbine on 140 lb. pressure has been added, also one 1000-kw. low-pressure turbine, using exhaust steam from the engines. Condenser equipment, including three large cooling towers, has been provided for the turbines.

Nine sub-stations are now in operation, and three 500-kw. step-up transformers, 6600 to 22,000 volts, have been installed for supplying mines to be opened about 12 or 15 miles distant.

A very economical plant has been installed near Fairchance, Pa., utilizing in the boilers the waste heat from the coke ovens. A large flue is built back of 100 bank ovens, with smaller flues connecting each oven, and a boiler plant is located at the center of each section of 50 ovens. Thus each boiler plant draws from 25 ovens each way, making a travel of about 350 ft. for the hot gases. The engine room is half way between the boiler plants, and contains four 400-kw., 2300-volt, 25-cycles, three-phase generators, driven by cross-compound engines. By means of five sub-stations this plant now supplies seven works, operating locomotives, larry equipments, car hauls, conveyers, fans, pumps and coke-drawing machines. Up to the present time it has been found necessary to operate but one boiler plant, but extensions are under way which will absorb the entire capacity of the plant, one of the additions being a 1000-cu. ft., 1000-lb. motor-driven compressor for supplying air locomotives in a gaseous mine. When the demand for power increases, it is expected to install a low-pressure turbine with condensers, which would give about 1000-kw. additional when operating three engine units.

At Ellsworth, Pa. it was expected ultimately to install an alternating-current central station, and belt-driven synchronous converters were installed for temporary use as three-wire direct-current generators. A neutral was obtained from the collector rings through the secondaries of small 200-volt transformers, and this neutral was permanently grounded to the mine tracks. Locomotives, machines, and pumps were operated at 275 volts between either main lead and the track, the load being balanced as nearly as possible, while outside motors, on fans, etc. are connected across 550 volts. It was found that straight star connections to the neutral from the collector ring through transformers would not work, as the converters bucked badly until interconnections were made to neutralize the flux in the transformers due to unbalanced direct current. It was also clearly demonstrated that the old style converters are much better adapted for use as direct-current generators than the modern design. The first ones installed were built 7 or 8 years ago and operated well with proper attention. One or two new ones could not be operated successfully at more than one-half rated capacity.

Three-wire, direct-current plants are also in operation in West Virginia, using railway type generators, with derived neutral through balancing transformers. One of these plants, at Minden, W. Va., operates three 300-kw., 600-300-volt generators, driven by cross-compound engines, and supplies four mines. The apparatus in use includes 20 locomotives, 16 machines, 21 pumps and 14 fan, car-haul, and miscellaneous motors.

The three-wire system has the advantage of being less dangerous than that using 550 volts pressure; the return or bonding need not be so good, and motors, etc. stand up better. The two voltages are also useful for variable-speed requirements. It is objected to on account of the care required in balancing the circuits. As a transmission problem, it is, with perfect balance, a 600-volt metallic circuit, and therefore requires just twice the copper—neglecting the difference in bonding—as a 600-volt, grounded-return system, or half the copper as compared with a two-wire, 300-volt grounded system. The balancing is most effective when a large number of small units are operated. The unbalanced current at Minden rarely exceeds 15 per cent.

In Woodward, Alabama, a plant has been installed at the furnaces of the Woodward Iron Company, taking steam from the furnace boiler plant, normally fired by blast-furnace gas. The plant includes three 400-kw., 3500-volt, 25-cycle, three-phase generators, with cross-compound engines. At or near the furnaces two two-stage turbine pumps, delivering 3000 gal. per minute each against a 135-ft. head, are operated for furnace use, while two 100-kw. motor-generator sets supply 250-volt direct current to shop motors, small locomotives handling ore wagons, and a travelling crane handling hot iron on the casting floor.

At No. 1 coal mine, about 2.5 miles away, the current is taken underground in a three-conductor, varnished-cloth insulated, steel-armored cable. Four thousand feet inside are two 700-gal. triplex pumps chain-driven by two 150-h.p., 3300-volt, induction motors and working against a 550-ft head. A few thousand feet farther in is an endless rope haulage, chain-driven by a variable-speed, 3300-volt motor, running at 200-480 rev. per min., with a controller and secondary resistance. About two miles from the pit mouth is an underground sub-station, containing one 200-kw. converter with step-down transformers, etc., supplying 275-volt current to mine locomotives. A number of small triplex pumps, operated by 440-volt induction motors, are also in use.

At No. 2 coal mine, about two-thirds of a mile farther from the power plant, current is taken underground approximately two miles to a duplicate sub-station, also supplying locomotives, and up an air shaft to a 50-h.p., 3300-volt motor driving a mine fan. On account of the frequent labor troubles in that district, it was not advisable to take any power overhead, except along the railroad to the coal mines, where the line could be patrolled.

The plant is now being enlarged to provide power to the ore mines, three miles from the plant in another direction, to operate hoists, crushers, pumps, and air compressors for rock drills.

The six 150-h.p., 3300-volt motors on turbine pumps, triplex pumps, and motor-generator sets are duplicates. The underground cable is suspended from a messenger wire, with frequent loops for expansion and repair. There have been several rock-falls on the cable, most of which have caused short-circuits, but repairs are easily made. The armor is protected against corrosion by a layer of jute and asphalt, but the miners have cut a good deal of this off for kindling to start fires. They also stole about 40 gallons of oil out of the substation transformers one night, for use in their lamps.

These mines go in on a slope of about 20 per cent for the first mile, after which the vein flattens out. There is only about 4 ft. of headroom. A good deal of the underground apparatus was skidded down on the track rails.

At Ehrenfeld, near Johnstown, is a plant in which belt-driven converters were first used for generators, supplying an underground substation through step-up transformers from 165 to 5600 volts. This substation contained, besides the necessary step-down transformers, one 250-kw., 275-volt converter, operating on the trolley in parallel with the direct-current side of the double-current generators. This was the first alternating-current plant operating underground substations. Larger direct-connected generators have since been installed. It was the intention to use the original generators as converters later.

At Yatesboro, Pa., there is a successful installation, operating a number of motor-driven compressors, fans and sub-stations. The station equipment includes two 1500-kw., 60-cycle turbine units, generating three-phase current at 6600 volts. In two substations are installed 300-kw., 550-volt converters running at 900 rev. per min. and in a third a motor-generator set, with an induction motor driving a 300-kw., 550-volt generator. Three motor-driven fans are in use at different mines, one with a 250-h.p. motor, belt-driven, one with a 250-h.p. motor and silent-chain drive, and a third with a 400-h.p. motor direct-connected through a flexible coupling. There are also, at the various mines, eleven 1400-cu. ft. duplex compressors, belt-driven by 250-h.p., 6600-volt induction motors. One interesting feature of this plant is that these high-tension induction motors are all started by throwing directly on the line.

At Windber, Pa., there have been operating, until this year, eight direct-current power plants supplying 12 mines. Two of these plants, those at No. 36 and No. 40 mines, are efficient installations with cross-compound condensing Corliss units, water-tube boilers, etc., but the range of distribution was such that the loss in transmission overcame the efficiency in the plants.

In most of the mines locomotives only were operated, at 550 volts, and the transmission was from 1.5 to 2.5 miles. Compressed-air "puncher-type" mining machines and compressed-air pumps were used, with steam engine-driven fans. It was decided to centralize the power, to do away with all the direct-current power plants, except No. 36 and No. 40, and to limit their field to a radius not exceeding 1.5 miles. The boilers from some of the dismantled steam plants have been assembled and a plant installed at No. 35 mine, in nearly the center of the field. The equipment includes one 400-kw., 6600-volt, three-phase, 25-cycle generator, driven by a cross-compound engine, and two 1000-kw. steam-turbine units to operate at 140 lb. pressure and 1500 rev. per min. One additional turbine unit, probably of 3000-kw. capacity, will be installed early next year.

The 400-kw. engine-driven unit, with two 200-kw. converters, was purchased some years ago. These converters with one additional, will be installed at No. 38 mine and also supply No. 39. At No. 33 mine and also to supply the front end of No. 34, will be located two 150-kw., belted-type, 550-volt generators, formerly used at No. 30, now to be direct driven by 225-h.p., 6,600-volt synchronous motors at 500 rev. per min. In this substation will also be installed one 1800-cu. ft., 2-stage air compressor, direct-driven by one 300-h.p., 6600-volt, synchronous motor at 187 rev. per min. In a substation at the back end of No. 34 mine, also supplying No. 31 mine, will be located one 300-kw. converter and two direct-driven 1800 cu. ft., 2-stage compressors.

At No. 41 mine electric puncher machines are supplied with 250-volt current from a 100-kw. generator driven by a 150-h.p. 440-volt induction motor at 750 rev. per min.

At No. 42 mine two 300-kw., 550-volt converters are installed, to operate locomotives in two drifts, one in each vein of coal, and also to feed into the back end of No. 36.

At No. 35 shaft, two miles back from the pit mouth is located a large fan to ventilate No. 35 and parts of No. 36 and No. 40. This fan will be driven by a 400-h.p., variable-speed, 6600-volt motor, direct-connected through flexible coupling, to operate at 200 to 285 rev. per min. A substation here contains two 300-kw. converters, with space reserved for one more, also six 150-kw. transformers, with a 6600-440-volt ratio supplying two large pumps at the shaft bottom. A drainage level was located across mines Nos. 37, 40, 35, 36 and 42, all the water above which will flow by gravity to this shaft. Here will be placed two two-stage turbine pumps, each of 4000-gal. capacity per minute against a 330-ft head, and each will be driven by a 500-h.p., 440-volt induction motor at 730 rev. per min. These pumps will replace over 70 compressed-air and steam pumps.

A sub-station will be located at the rear end of No. 37 mine, and contain one 300-kw. converter, and later one motor-driven compressor. This converter will work in parallel with No. 40 direct-current plant, supplying the outside haulage, etc.

An induction motor has been designed for the electric coal puncher, or "pneumelectric" machine, and it is expected, if this proves a success, to replace the compressed-air punchers wherever found practicable. On account of the large investment in machines, pipe, etc. some mines will still be operated by air, as No. 33, 34, 31, 37 and 40, and wherever necessary for best economy motor-driven compressors will be located near the work, displacing steam-driven machines.

The output of these mines is normally about 18,000 tons per day. The cost per ton has been slowly but steadily increasing from year to year, as the mines advanced, and transmission lines and water lines lengthened. It is expected to increase this output as desired to over 20,000 tons per day, and to reduce the cost at least 6 cents per ton. This cost should then increase but very slightly for probably the next 5 or 10 years.

The cost of the electrical equipment, including foundations, buildings and installation, will approximate $250,000, and the total cost of improvements, such as shafts, drainage tunnels, etc., will amount to about $600,000.

## DISCUSSION ON "ELECTRICITY IN MINES." PITTSBURGH SECTION, NOVEMBER 10, 1908.

**F. L. Sessions:** I should like to suggest, what is not entirely original, a basis for the rating of mine locomotives as follows: the motor capacity shall be equal to a stated horse power per ton of locomotive weight per mile per hour at a stated speed in miles per hour, at 75 degrees cent. rise of motor temperature as measured by thermometer after a 1-hr. run.

Or, as an alternative which will refer strictly to the locomotive performance at the draw-bar: the rating of an electric mine locomotive shall be based upon the horse power per ton of locomotive weight per mile per hour at a given speed in miles per hour developed at the draw-bar continuously for an hour, with a rise in temperature of any part of the motors of 75 degrees cent.

**W. A. Thomas:** The exhaust-steam turbine will be of considerable importance in the near future. A number of plants have been equipped, and many more low-pressure turbines might advantageously be installed where the exhaust steam from reciprocating engines is being wasted. In the case of one coal company, since putting in exhaust-steam turbines 1,000 kw. have been recovered on four units, whereas formerly not more than 200 kw. in heating value were obtained from the exhaust of the engines. This economy is bound to become a marked feature in general work as well as in coal-mining operations.

The standard of laws for the use of electricity in mines, that has been considered in the establishment of laws in Pennsylvania is similar to that established in New South Wales. Electrical men who are associated with mining operations should make themselves familiar with these laws.

Probably one-third of the restrictions and special limitations in the New South Wales laws are on account of defective insulation on the wires, and as good insulation is used there as can be obtained in this country. In this country it is usually considered that up to 600 volts the wires should be left bare. In establishing rules in this country I believe it will eventually be decided that bare wires should be used and that we should not trust to insulation.

I agree fully with Mr. Sessions in his ideas on standard ratings. I think that concerted effort should be made on the part of the manufacturers to get mining men who are interested in electrical matters to comprehend more fully what an electrical rating is, and then come to a common basis, as it is confusing to an operator if he is not acquainted with these matters.

**H. W. Fisher:** The destruction of the lead covering of cables by acids in mines has been repeatedly brought to the attention of the manufacturer of cables. At present we are experimenting with a form of cable which is protected by the use of a high melting compound which is practically acid proof. In making this cable the strand is first coated with the compound, so as to prevent moisture from entering the cable along the strand in case the ends are not especially well protected. Then varnished cloth is applied to about the necessary thickness for the voltage in question, after which a layer of this special compound is applied, then one or two layers more of varnished cloth, and over these the usual braids.

We also make a rubber-insulated cable which is finished with a layer of special black compound and varnished cloth and braid as above specified. These forms of cables have only recently been put on the market, but sufficient time has not elapsed for us to know definitely if they are giving satisfaction.

*A paper presented at the 231st meeting of the American Institute of Electrical Engineers New York, November 18, 1908.*

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# ELECTRIC HEATING

## BY W. S. HADAWAY, JR.

It may assist in a better understanding of the terms used in discussing electric heating to state at the outset that the words heat, potential, etc., are employed more specifically than has generally been found necessary in discussing heat effects apart from electricity. Heat, like electricity, is assumed to flow from a surface of high potential to one of low potential. Quantity or volume of heat is analogous to quantity of electricity. Unit quantity is here figured as the British thermal unit, though for technical purposes it is, of course, the calorie. Temperature corresponds to potential. Heat potential is as true an expression of potential as is impressed electromotive force; it should not, however, be confounded with static potential, a term used in discussing energy of gas. It would materially simplify thermal nomenclature if a word were coined to designate heat potential in the same manner that electromotive force expresses electrical potential.

The term "electric heating" is commonly used to express the frittering down of the higher potential energy of electricity into the lower potential energy of heat. There is no well defined line of demarcation; the result is inseparable from the conveyance or utilization of electricity in any degree. The expression is, therefore, a meaningless one from the heat engineer's standpoint and it fails accurately to express the performance of useful work by the transmission of heat energy to a distance by means of electricity. The expression, "electricity, a factor in a telethermic system," would be a better definition, but for obvious reasons the shorter and simpler expression is employed.

Heat energy is to be regarded as a commodity that can be generated or controlled in convenient form and distributed and sold, and in which electricity is used either directly as the high-potential heat factor or indirectly as agent. The distribution and application of heat energy by electricity to arc and incandescent lighting, to metal welding and forging, and to electric furnaces for various industrial operations are illustrations of results already attained in electric heating and are properly discussed under the broad interpretation of the subject.

The feature of the subject we are to consider is the practical adaptability of commercial electricity for heating purposes and for performing useful work under the conditions imposed in general industrial and domestic life, apart from the specific adaptations previously mentioned, and particularly in connection with other heat distributors for a multipotential heat supply.

These applications may be roughly divided into two classes according to the degree of concentration of the heat energy used. The first class includes low-temperature heating, generally diffused and in large volume; the second includes high-temperature heating, generally localized and in small quantity.

In heating on a small scale no adequate classification is possible; it is the blending of high-potential heat energy into low-potential heat work for many useful operations that primarily suggests the feasibility of heat transmission by electricity. An arbitrary line of temperature demarcation for heating on a large scale has been drawn at 250° fahr.

The closest common analogy to the differences between low-potential, large-volume and high-potential, small-volume heating is the distinction between volume and pitch in sound. As examples of the first class may be cited the heating of rooms and of water at atmospheric pressure; examples of the second class are electric ovens, sad-irons, and soldering-irons.

The electrical unit or kilowatt-hour is the equivalent of 3412 British thermal units. For practical purposes the work in hand is to determine the useful work in different lines obtainable from this number of heat units at a fair average cost of supply. There is involved indirectly the determination of relative efficiency between electric and other methods of heat generation, distribution, and application.

To show what the heating efficiency of different methods of application may mean, the following experiments, reviewed in the London *Electrician* for Nov. 2, 1894, are cited. The determinations were the relative heating values of combustion and electricity by resistance. The same wires were heated, first in a flame and then by electric current. It was found that with a platinum wire held in a flame less than 0.5% of the thermal energy produced in the flame was transferred to the wire, while 90% of the electrical energy used appeared as heat. In another case an iron bar weighing about 20 lb. was heated by charcoal and then by electricity. In the former case about 0.75% of the thermal energy was transferred to the bar and in the latter case 88%. It is evident from the description that the calorimetric methods employed were rough, and the results are quoted more as qualitative than quantitative determinations.

It should be observed that the foregoing illustrations are examples of the second class of heating applications; figures tabulated farther on will show results obtained in water heating by various methods of heat application, which are as true examples of efficiency tests as the preceding but in the first class of heating. The heat capacity of the work performed is sufficiently large to express the relative differences in combined efficiency, and, as we should expect, the lower the temperature of the work, the larger the area heated; and the greater the capacity the less the difference in ratio between heating by combustion and by electricity. We may readily determine the conditions where the ratio is an inverse one.

In room-heating apparatus on continuous run we may estimate that one watt-hour, 3.41 thermal units, will heat one square foot of common radiator surface through 1.26 degrees fahr.; that 1000 watt-hours or 3412 thermal units will heat the surface approximately 126 degrees fahr. above the room temperature; that is, for room heating from 85 to 110 watt-hours are practically the equivalent of steam at low pressure condensed by one square foot of radiator surface with the difference between the room and the radiator temperatures as above stated. This, of course, takes no account of the heat capacity of the apparatus, which is practically eliminated by the imposed conditions of continuous running. We may safely assume that a fair average price of the electrical unit from large steam electric stations is 6.7 cents. It would therefore cost 0.65 cents average to run one square foot of direct radiation surface for one hour, or the electrical unit would keep about 10.3 sq. ft. of radiator surface at the temperature difference noted for one hour.

Direct comparison of this value with practical steam heating is difficult, owing to the variables involved. We may, however, compare it with a central station steam distributor as quoted by Unwin in his work on the " Development and Transmission of Power," referring to a New York steam company.

The unit of heat used by this company is defined as the " kal ", which is stated to be the heat required to evaporate one pound of water from 100° fahr. at 361° fahr. or at 85 lb. pressure per square inch. One kal is therefore about 1110 thermal units. On a sliding scale the charge is stated to be 70c. per 1000 kals to small users, and 40c. per 1000 to large users. As the price of 6.7c. per electrical unit is to a fairly large user, we shall compare it with the 40c. per 1000 kal rate. For 40c. the consumer obtains 1,110,000 thermal units from the steam station, compared with 20,400 thermal units from the electric station, a ratio of nearly 54 to 1, or practically 50 to 1 as a loss must be figured in the case of steam, dependent upon the temperature at which the condensed water is allowed to escape.

It is interesting to note in passing that while the relative efficiencies of generation are about as 12 to 1, the commercial rates quoted are as 50 to 1. The ratio of the cost of heat energy from the electric station to the cost from the steam station is therefore practically four times as great as the ratio of the relative costs of production. This disparity should be considered in discussing the influence and importance of the load-factor as discussed by Crompton in his paper on " Electric Energy."

Clearly, the steam-driven electric light station ranks low as a heat distributor for house warming on any considerable scale. And yet notwithstanding the great disparities in the cost of heat energy on a large scale, the uses to which small electric air heaters are put are surprisingly numerous. We are all more or less familiar with the use of gas stoves for room warming, but it has been found by wide experience that the electric air heater for auxiliary room warming, for bath and dressing rooms, for libraries, cabins on yachts and steamships, in mild climates in early morning and evening, etc., serves its purpose with fair economy, and without vitiation of the air and by-products always evident from gas.

It is then on a comparatively small scale and in intermittent service that the electric air heater is useful when power is derived from the steam electric station and when the heat supplied is derived from the electric resistance. It is interesting to note that the relative costs of copper and structural steel differ in nearly the same proportion as the generation costs of electricity and steam. And while we use steel as the frame-body, and copper to round out and embellish the structure, so may the relative value of electricity to steam be regarded in heavy quantitative heating work.

This discussion does not include heat storage systems from hydroelectric installations which have been described briefly by Mr. Chas. E. Waddell*. Where an equipment is utilized for only 50% to 60% of the day, and water storage is not required, there are opportunities for broadening out electric heating applications by absorbing the energy of the plant in heated water, which may be employed in combination with high-temperature heaters at periods where under other conditions the loads would overlap. It is evident that this method of supplying the low-temperature component of a heating system must be resorted to before electric cooking which includes hot water in considerable volume, can be generally successful.

While considering the use of electricity in diffused heating on a large scale, we should not overlook the deductions made by Lord Kelvin "On the Economy of the Heating or Cooling of Buildings by Means of Currents of Air" and published in the Glasgow *Philosophical Proceedings* Vol. III for Dec. 1852 and followed by mathematical demonstrations in the Cambridge and Dublin mathematical journal for Nov. 1853. Quoting from these articles:

> In the mathematical investigation it is shown that according to the general principles of the dynamical theory of heat any substance may be heated 30 degrees above the atmospheric temperature by means of a properly contrived machine driven by an agent spending not more than about 1/35 of the energy of the heat thus communicated and that a corresponding machine or the same machine worked backward may be employed to produce cooling effects, requiring about the same expenditure of energy in working it to cool the same substance through a similar range of temperature. When a body is heated by such means about 34/35 of the heat is drawn from surrounding objects and 1/35 is created by the action of the agent; and when a body is cooled by the corresponding process the whole heat abstracted from it, together with a quantity created by the agent, equal to about 1/35 of this amount is given out to the surrounding objects.

We have thus introduced refrigeration as well as heating by electricity as agent. In editing his mathematical and physical papers, Lord Kelvin added the following interesting note under the date of June 26, 1881:

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* Proceedings A. I. E. E., July 1908, p. 1197.

The method of cooling air in unlimited quantities described in this article has been realized by Mr. Coleman, first in refrigerators used for the distillation of paraffin and after that in the Bell-Coleman refrigerator for carrying supplies of fresh meat from North America to Europe; in a great refrigerator recently sent out for the Abattoir at Brisbane, Queensland. The Bell-Coleman machine sends large quantities of air cooled to 10° or 20° C. below the freezing point into the chamber to be kept cool; and the general temperature of this chamber is thus maintained at the desired point.

The method of heating air described in the article remains unrealized to this day. When Niagara is set to work for the benefit of North America through electric conductors it will no doubt be largely employed for the warming of houses over a considerable part of Canada and the United States. But it is probable that it will also have applications, though less large in other cold countries to multiply the heat of coal and other fuels, and to utilize wind and water power (with aid of electric accumulators) for warming houses.

In Anderson's treatise on the "Conversion of Heat into Work,"* will be found descriptions of compressed air refrigerating machines made on the principle above described, and in Professor Peabody's work on the "Thermodynamics of the Steam Engine," pages 464 and 465, will be found tests on a Bell-Coleman refrigerating machine. The use of electric motors in refrigeration has been under consideration of central station men for some time, being advocated by well known engineering authorities; but so far as the writer can learn nothing whatever has been accomplished in the use of motors for heating purposes.

Lord Kelvin's deductions on using electricity as agent for warming purposes have been advisedly introduced into this discussion. His conclusions may prove to be wrong until more perfect thermal insulation is developed, but to anyone familiar with thermodynamics and electrical development the possibility of using a positive force to control and direct a less definite form of energy must appeal with singular emphasis.

It may be that the electric furnace using low-grade carbon in high-temperature combustion chambers will give the desired results. Tests indicate that the only obstacle to this latter combination is in making the apparatus "fool-proof." The need for more economical use of fuels and the fact that electricity by resistance heaters is an ideal high temperature component make the development of the low-temperature factor imperative for a complete combination.

When electricity is derived from water power we might expect a far wider availability of energy from heat of resistance for applications requiring heat in large volumes than when electricity is derived from steam power. Careful deductions show that for house warming the cost of a horse power year must not exceed $6.00 in order to compete directly with high grade coal at $5.00 per ton.

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* Third edition, pages 189 and 194.

Statistics compiled by Professor Geo. F. Swain show that the average cost of the mechanical horse power-year from water power in this country is about $10.00; to this must be added electrical generation and transmission charges, which make it seemingly impossible to realize a figure for electrical energy delivered that will not be greater than the cost of heat directly from fuel. The compensating advantages in regulation and control, combined with the improved load-factor, especially in combination with thermal storage work, warrants the extensive use of the heat of resistance for house warming at least within restricted areas. In the case of hydraulic plants with large water falls, where the capital charges are relatively low, we may expect many extensive applications of room heating on a successful basis.

In his paper on "The Cost of Steam Power",* Mr. C. E. Emery cites the case of Lawrence, Mass., where with moderate fall the cost of a horse power-year from water power is figured at about $25.00, or practically the same cost as power generated from steam. In the practical treatment of this question, local conditions will control the breadth of applicability, including in these local conditions cost of electric power, cost of coal delivered, extremes of climate, average humidity, etc.

We have still another source of electrical energy to consider in connection with low-temperature diffused heating, in which power is derived from gas, oil, and air engines. In a lecture before the Royal Institution in April, 1893, on the "Utilization of Energy," Professor Kennedy places the theoretical efficiency of coal gas at 80%. Of this a gas engine, he says, utilizes from 22% to 32%. For diffused heating it is apparently more economical to distribute the gas directly than to attempt to convert its energy into electricity. Attention is further called to the paper by Mr. Williams before the Society of Arts, Boston, Mass., on May 10, 1894, in which comparative costs of coal and various fuel gases are given, and in which it is shown that the gas equivalent of coal may, under most favorable circumstances, cost eight or ten times as much as coal.

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* Transactions A. I. E. E., March 1893.

The consideration of the relative values of gas and electricity for heating purposes is a matter that can only be inadequately discussed here, for the problem is a complicated one and demands the most thorough consideration. We must not underrate the facility with which gas may be stored, the economy of rapid and continuous generation, and available heat from combustion and discharge of by-products, whereas in electric lighting and electric heating every unit of light and heat secured represents an appreciable loss or depreciation of the energy converter.

There are many advantages to be considered on the other side such as localization, immersion of heater in working chamber, as in ovens, sad-irons, and water heaters, freedom from bi-products, etc. In electric heating and cooking for domestic uses the real difficulty is how to provide a hot-water supply economically. The same thing is true in the use of gas, though in a lesser degree. On a broad scale it appears easier to arrange for this on a multipotential heat supply system than on any system using gas.

In his treatise on gas engines, Donkin shows examples of these engines of large size furnishing power at rates less than can be obtained from other prime movers. For high-potential heat distribution from isolated plants this form of energy transmitter is generally available; but it may be seriously questioned whether in isolated plants for domestic use the hot water supply as usually provided can be economically heated, unless of course the combined economies permit the use of individual gas-heated water supplies.

It may be safely concluded from the foregoing illustrations that we cannot afford to use electricity for general diffused heating purposes on a large scale. It is proper to point out, however, that practical experience shows that these deductions may lead to unsafe conclusions. There are many striking analogies in heating development to the working out of the electric motor.

If we were to take the case of an engine in a factory and substitute for it an electric motor we would not expect, with our present knowledge of this subject, to effect marked economies. We know that we depend upon the elasticity of the small motor to produce results and that the combined load of a number of individual units reduces fixed losses and increases output. It is the same in heating. We must consider the individual applications, and the combined results of these will be far different from any considerations controlling a fixed system. One of the reasons contributing to the slow growth of electric heating development is the necessity in many cases of devising apparatus to do work more effectively than could be done by the old methods.

On the other hand, the collective strength of these new methods has given the work a standing, in the industrial lines particularly, which constitutes an advance in heating development. It has further been shown that results may be obtained which make the cost of operation of secondary importance than if considered solely on basis of thermal values.

The British thermal unit is the equivalent of 778 foot-pounds of work, and we would obtain as much heat by applying a brake directly to the fly-wheel of the engine or prime mover as we obtain from the heat of electrical resistance, which so far as its results go may be considered as friction. If we use as an average thermal value of a pound of coal 14,500 B.t.u., we can secure 9400 units in a good steam boiler, or practically 65%.

There are many cases in practice in which this efficiency is exceeded, but Thurston's figures give 65% as a fair average value. The fuel efficiency of the steam engine rarely exceeds 10%, and the heat incapable of conversion into high-potential energy represents about nine-tenths of the whole, notwithstanding the fact that over six-tenths of the thermal energy of the coal are obtained in useful work in the boiler.

It is therefore to this point we should look for our large volume heat supply, and we find in actual practice many illustrations which show that no great engineering difficulties are encountered in distributing the boiler energy and also that of the exhaust steam from the engine for useful work at a distance. The New York steam company's plants already referred to are distributing energy by live steam for heating and power purposes at about 80 lb. pressure. The leakage and radiation losses are stated to be estimated at about 15%, yet with this loss the heat energy can be delivered on a successful and economical basis.

The work of Birdsill Holly since 1877 in carrying out central station heat supply is too well known to require explanation. It is important and interesting in connection with our problem since it shows that central station diffused heat supply is entirely feasible. We are now able to formulate a multipotential heat supply system in which the steam, either live or exhaust, or both, is used for low-temperature work, and electricity from generators in the same station is employed for all work requiring temperatures in excess of that of the steam; that is, from about 250° fahr. upward. In domestic work the steam heat would be employed for house heating and water heating for bathing, laundry, and cooking purposes. Electric heat would be used for lamps, ovens, broilers, small stoves, sad-irons and all purposes requiring a high temperature localized heat. And a feature of such a combination not to be overlooked is the facility with which ventilation and heat regulation can be secured, since all the elements are at command to force an abundant supply of heated pure air through the building to be warmed. There are no new or untried features in such a combination; practically all of the elements necessary for the work are already employed though in a somewhat disjointed form so far as complete flexibility of heat supply from one center of distribution is concerned. If we refer to the *Electrical Engineer* for April 5, 1893, there will be found a description of the Springfield (Ill.) electric light and steam distribution plant. In operating this plant the exhaust steam is used for warming buildings, but there appeared to be no systematic effort made to carry out a multipotential heat supply.

As bearing upon the historical development of this matter the author quotes from a letter from the American District Steam Co., of Lockport, N. Y., in 1894:

> We observe that you recognize the futility of electricity competing with steam for diffused heating, but there is a wide field for electrical companies in connection with their exhaust. In blocks of buildings where power is required to run elevators, or for other purposes, the proprietors will run their own power if they have to do their own heating, but if the electric company can heat the building it can get the power at a good profit and there is a profit in both heating and power.
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> We have just constructed a heating plant for the Rochester (N. Y.) Gas & Electric Co., who are doing just this thing; they start off with 5,000,000 cu. ft. of space to heat in manufacturing and business blocks, and secure the running of several engines in the same buildings. They supply the steam from their stations in underground pipe and power by wire. They could not get the power without doing the heating. We think you will find this a fertile field for investigation.

Citations of events in 1893 and 1894 are made advisedly as having a bearing on the development of the art. It was found that while a business could be built up along these lines that there was a great deal to do in developing heating appliances to make them sturdy and effective, and that it would be necessary to choose the industrial isolated plant as a more immediate field for both heat engineering and appliance development.

Careful study of the question of multipotential heat supply, from both engineering and business standpoints, can hardly fail to give the utmost confidence that results of the greatest value can be obtained along this line. A total fuel efficiency exceeding 35% for both low- and high-temperature heating is certainly attainable, and probably a still higher efficiency may be secured from operations on a large scale. It is in this direction that we must look for the best immediate results of electric heating in domestic life. Electrical engineers realize that the ordinary light and power station is wasteful as a heat generator and distributor, and one of the ways to improve these conditions is to introduce a basis of supply in which the load-factor is a larger percentage of the station capacity and in which low-temperature steam distribution may also be utilized. This study deserves the greatest possible care and while data are occasionally available there is still much to be learned.

In the modern apartment house we find it possible to effect a comparatively high distributive heat efficiency. The rooms are heated by low-pressure steam or hot-water radiation and the hot water for laundry, bath-room, and cooking purposes is also supplied.

Electric lighting is available, but low heat efficiency is found in cooking except in cases where gas is available. No one can question the value of gas as a fuel in cooking; we may however take the ground that when a boiler plant is required for room and water heating, and the electric plant for lighting, the use of gas in cooking is unnecessary and comparatively expensive, for it is a form of heat supply not as effectively localized as electricity and is accompanied by many disagreeable features.

In these houses electricity is already in use instead of alcohol for heating conveniences, also for heating sad-irons for laundry work and pressing; and it appears to be a question of time only when electric ovens and other cooking utensils will replace the range or the gas stove on a considerable scale. The apartment house supplied with its own boiler and electric lighting plant, approaches more closely the proper conditions for electric heating than any other mode of domestic life, as all the conditions essential to economical working are already present.

The foregoing deductions have been introduced to indicate broadly wherein the true economical basis of electric heating lies. Like all general considerations they are qualitative rather than quantitative in character. We find in industrial and commercial practice a great number of heat applications, either at high or moderate temperatures, in which close regulation and facility of control are necessary and where electric heating on some scale is applicable.

The introduction of electric lights and motors has brought into use in central stations and isolated plants a vast amount of electrical generating apparatus, so that at the outset our problem is largely one of applying electric heating apparatus on circuits already established, primarily for other purposes. On these circuits we are usually able to supply apparatus to do the work required better than it is at present accomplished. First cost and cost of operation are not the sole considerations in any apparatus; in addition to the cost, the collateral advantages derived from its use must be considered.

In domestic work there have been large numbers of household conveniences sold, notably electric sad-irons. Perhaps novelty was in many cases the reason for first purchase and use, but once used the value of the method of heating is well appreciated and extensions are made to more and different work. In this slow and conservative way electric heating in households is progressing, and there are indications of a more rapid general reception and use.

There are some installations in which all or nearly all the cooking is done by electricity. These are generally successful and economical, according to the degree to which extensive water heating is eliminated. Laundry and pressing irons are found almost uniformly satisfactory. Some of the devices used in the dining-room are counted great conveniences when electrically heated. When it comes to the kitchen the same feeling of cleanliness and refinement of methods as for the dining room is expressed and hoped for, but the housewife is not so intimately in contact with the apparatus and ignorant manipulation is encountered, which, however, generally does no other harm than to add to the expense of running. But fortunately the manipulation and control of the devices is so simple and saves the servant so much work that an honest effort is usually evidenced to use it economically.

In industrial work the progress of electric heating has been more rapid than in domestic applications, with the exception of the electric sad-iron. There are cases where heating by electricity is found cheaper than by fuels, setting aside all collateral advantages. In electric cars the more equable distribution of heat; on a satisfactory basis of effective warming is sufficient to employ the method and apparatus even at considerably greater cost than former methods of heating.

We have before us for the future two methods for the distribution of heat; the first, a multipotential heat system in which steam and electricity simultaneously are the means of transmission; secondly, a constant-potential heat system in which electricity is employed as an agent for diffused heat work in large volume, and the heat of resistance, either directly or with the additional heat of combustion of carbon, is used for high temperature purposes. The first is a combination of well known engineering practices and represents elements in successful use at the present time.

The second method is more difficult, as it includes new methods of applications and untried apparatus. For the present we have to approximate the probable final conditions by using materials at hand so far as they will go with reasonable economy, using every energy to broaden the general conception of the help and convenience arising from central station heat supply.

It has been thus far assumed that the development of electric heating depends solely upon engineering conditions without reference to the state of the art of the appliances themselves. Unfortunately the lack of sturdy resistances of high rates of heat impartivity has materially retarded commercial progress. Factors of safety have been too low and rates of working too slow. We are still without a satisfactory heat insulation and in practically the same position as the electrical industries prior to the use of mica.

A circular gas burner will impart heat at a rate equivalent to 35 watts per superficial sq. in. Electric stoves made for 110 volts will work about one-third this rate. This is a serious hindrance to electric cooking and high temperature applications. Far better apparatus could be made for lower voltages, and in this respect the state of the art closely resembles the situation of tungsten and tantalum lamps which are simply high temperature heating applications.

Since Dr. Lindeek's paper on "Material for Wire Standards of Electrical Resistance" was presented before the International Electrical Congress in Chicago in 1893, the only alloy that has been offered for resistance purposes is the nickel-chromium product; that is, in fifteen years, notwithstanding the marked development in electrical furnace work, there appears to have been but one new alloy brought out in commercial form.

Attention is called to these points to emphasize the need of further research work in materials and processes for good commercial work. The heaters on the market to-day are greatly improved over the product of fifteen years ago but there are still wide gaps to be filled. Localization of heat at high temperatures with negligible heat capacity are the prime requisites of an electric heater. Without adequate heat insulation, with resistance material of comparatively low specific resistance and high voltages in commercial practice the average design is far removed from the ideal.

## DISCUSSION ON "ELECTRIC HEATING." NEW YORK, NOVEMBER 13, 1908

**Charles E. Waddell** (by letter): Dividing heat applications into low-potential quantity and high-potential intensity types is a very expressive way of classifying two general conditions. In high-potential heating problems it has been demonstrated that the cost of electrical energy has little or no bearing on economy. Other factors enter that more than compensate for any discrepancy in calorific value between electricity and fuels; for example, electric glue cookers, laundry irons, and apparatus in printing and embossing plants. The field for this type of heating apparatus is decidedly small as compared with the field for low-potential applications; and it is this latter class that presents diverse conditions and offers fascinating opportunities for specific solution. Elusive in its nature, difficult to measure, and next to impossible to insulate, heat is in many respects a more subtle and difficult form of energy to control than is electricity. When comparing electric heating with fuels in the realm of domestic heating, the fact must never be lost sight of that by means of electrical measuring instruments the quantity of heat delivered by the electrical apparatus can be accurately determined; whereas in the case of fuel apparatus, while the calorific value of the fuel itself may be known, the efficiency of such apparatus is so variable and uncertain that its economy is largely a matter of conjecture.

It is doubtless true that the steam power plant, by reason of its low efficiency, is forever debarred from furnishing electric heat in competition with fuels. In the case of a thickly settled district, the use of exhaust steam for heating has been demonstrated as profitable and desirable; and, as Mr. Hadaway suggests, conditions may be such that it might be profitable to generate electricity for high-potential applications and use the exhaust steam for quantity work. It would appear that the scope of such a plant might be widened by applying the electric heat in districts too remote from the generating station to justify the installation of underground steam mains.

While the thermal value of a kilowatt-hour is very low (3412 B.t.u.) and electricity as a heating agent suffers by comparison with fuels, nevertheless it will not do to dismiss the whole subject as one unworthy of serious consideration. It must be remembered that the world's coal fields are being rapidly depleted, that natural gas areas are limited, and that wood as a fuel has even now virtually disappeared. Sooner or later electricity must necessarily become a factor in the field of heating. Where electricity generated from water power is obtainable, and where storage of the water through the night hours is impracticable, electrical energy for heating can be obtained at figures closely competitive with fuels. The problem in such cases becomes one of storing the energy of the water power in the form of heat, which brings up the all-important feature of heat insulation. Supplying electricity for heat as a by-product, with a view to maintaining a high load-factor on a plant, either steam or water, is a subject that will bear careful investigation in the majority of small steam and all hydroelectric plants.

In discussing boiler efficiencies, two factors are involved; first, the evaporative efficiency of the boiler; secondly, the all-day, all-season efficiency. Assuming a pound of coal has a calorific value of 14,000 B.t.u. and that under favorable conditions a given boiler plant can deliver 70 per cent to 80 per cent of this amount, the same plant in every day service seldom approximates 50 per cent of the calorific value of the fuel. As an instance of this, reference is made to the published data of a number of plants furnishing exhaust-steam heating where the annual average number of pounds of water evaporated per pound of coal is but seven and a fraction.* These data are not specific as to whether they mean the evaporation is from and at 212° fahr.; and since vague in this particular, assume the heat units per pound of water to be 1000, the delivered efficiency of the fuel is then seen to be but 7000 B.t.u. Here are cases where ostensibly the most expert supervision and attendance is provided; where the system is in a measure automatic; where the connected load in radiation is many times the capacity of the plant, hence a presumably high load-factor; and, finally, the demands are diverse, all tending to uniformity in load and consequent economy in fuel. If seven pounds of water is the best average result of large systems, the probable performance of the heating apparatus in an ordinary residence or apartment house is doubtless at an efficiency that is but a small fraction of the theoretical calorific value of the fuel.

Another point which I have had impressed upon me is that not only the quantity but the intensity of heat in domestic applications is essential to success. Formerly I attributed the asserted inferiority of the large, low-temperature electric radiator as compared with a small open fire to the idiosyncrasy or psychical peculiarity of the individual rather than to any physical difference. More recently I have revised my views, and I have found that in many instances a smaller quantity of heat, with which was blended an even smaller quantity of high temperature radiation, is extremely grateful. If electric heating is to be introduced upon a large scale into house warming, it will be necessary to accord the art of heating and ventilating more scientific attention than is now usually bestowed upon this class of work. Unquestionably, of the quantity of heat annually radiated in domestic installations the greater portion is wasted. Since the thermal value of a kilowatt-hour is fixed and not possible to increase, the general installation of this method of heating will be accompanied by economies in application.

The power engineer burns a pound of coal in a manner that will extract the greatest number of heat units in the shortest possible time. The heating engineer, while desiring the maximum number of heat units, endeavors to prolong the time as much as possible. As electrical heating apparatus is capable of delivering a uniform heat through any duration of time and at a maximum efficiency, it possesses an advantage that makes for economy.

The argument that heat obtained from electricity equivalent to that obtained from fuels is so high in cost as to be practically debarred from general use is scarcely logical in view of modern experience. The incandescent light, for instance, though more costly than either candles or kerosene lamps, has in a large measure supplanted both.

Finally, there is one other class of quantity work to which attention has not been directed and on which some remarks may be pertinent. In drying materials on a large scale—lumber, cotton yarn, etc., the heat that is supplied is merely a means artificially to accelerate a natural process. With a moderate amount of heat applied where needed and a skilful use of air currents, an apparatus more efficient than ponderous steam apparatus appears possible.

**W. N. Ryerson** (by letter): Mr. Hadaway has pointed out the limitations in the use of electricity for maintaining an equable temperature in buildings during the season of cold weather, and at the present time his remarks are undoubtedly to the point. There are instances, however, in which comparison between the use of electricity and other heating agents on the basis of cost leads to erroneous conclusions. An instance in point is the office building of the Ontario Power Company at Niagara Falls which was equipped, under the plans of the architects, with a low-pressure steam-heating system, having an auxiliary hot-air system with forced draught; the idea being to maintain a pressure in all of the outside rooms sufficient to prevent cold air coming through the cracks in the window frames, etc. The air in this auxiliary system was intended to be heated by a steam coil in the discharge of the circulating fan. Before this sytem was put in use, the writer designed an electric heater to take the place of the steam coils, and after having been in use for the last two winters it has been found that the low-pressure steam system is entirely unnecessary, a comfortable temperature being maintained in the coldest weather by the electrically heated hot air. It is true that the steam-heating system in this building is a part of a much more extensive one installed throughout the transformer building, of which the office forms an L, but it is not necessary to maintain a high temperature throughout the remainder of the building, with the exception of the switchboard room, which is heated by direct electric radiators. During the last winter it was found that the use of the boiler was only necessary for 25 days, and that during the remainder of the time the electric heaters in the office building and switchboard room were sufficient for all purposes.

The cost of this heater was $388.00 and it consumes 85 kw. (including power necessary for fan motor). In a plant of this size the cost of this amount of energy is negligible, whereas the natural gas and wages of boiler attendants form very real quantities. This heater supplies 72,000 cu. ft. of air space in a building exposed on three sides.

For the present and until some material capable of delivering heat at a higher rate than any resistive metal now known is found, the principal application of electricity will be in articles where the heating must be closely confined. The superiority of these articles is well recognized.

**W. S. Andrews:** It was my privilege to be associated with Mr. Edison while he was developing his low-tension, multiple-arc system of electrical distribution in the early 80's of the last century. I remember a statement that he made in 1881, to the effect that he expected to utilize the general distribution of low-potential electrical energy not only for public and private lighting purposes, but also for operating electric motors to drive the machinery in mills and factories, and for electric traction; furthermore, he confidently expected to make electricity generally serviceable for the cooking of food, and, to a limited extent, for the warming of dwellings.

We all know that Mr. Edison's prediction in regard to the use of electricity for lighting purposes was very quickly realized, and also that not many years thereafter the electric motor was developed to a considerable degree of perfection, and largely used. Heating and cooking by electricity, however, have failed to show a similar advancement, and a brief discussion regarding the probable causes of this delayed development may therefore be timely and profitable with the view of bettering existing conditions.

Let us consider the use of electricity for performing ordinary cooking operations. As Mr. Hadaway says, the real difficulty consists in providing a hot-water supply economically. At the price of 5 cents per kilowatt-hour, the cost of heating a gallon of water from faucet temperature to boiling at an efficiency of say 80 per cent is a little more than two cents, which to many people would be a prohibitive price, especially as the same results can be accomplished with gas for very much less. Apart from the question of water heating, however, the operations of baking, broiling, frying, toasting, etc., by electricity can be accomplished at a reasonable expense, when electricity is sold at the rate of 5 cents per kilowatt-hour, according to my own personal experience, taking into due consideration, as Mr Hadaway points out, the collateral advantage of being able to raise utensils to a high temperature with localized heat, thus keeping the kitchen much cooler in hot weather than is possible when using a coal or gas range. For several years past I have used electricity for cooking purposes in my home during the summer months. Water only was heated by a gas arrangement attached to the kitchen boiler, but all other heating and cooking was done by electricity at an average cost of $4.50 per month. I estimate that the average cost of heating water by gas amounted to about $1.50 per month, making an average total expense of $6.00 per month for cooking three meals per day for a family of four. This outlay also included the heating of water for laundry work and the use of an electric iron, so I do not think it can be considered as extravagant. My experience shows that an ordinary breakfast, including cereal, coffee, toast, and broiled meat, sufficient for two or three people can be cooked by electricity with an expenditure of about one kilowatt-hour, the various devices averaging as follows, on a liberal basis:

| | | | | | | |
|---|---|---|---|---|---|---|
| Cereal cooker | 600 | watts for | 20 min. | = | 12,000 | watt-minutes. |
| Coffee percolator | 600 | " " | 20 " | = | 12,000 | " |
| Bread toaster | 600 | " " | 10 " | = | 6,000 | " |
| Meat broiler | 1500 | " " | 20 " | = | 30,000 | " |
| | | | | | 60,000 | " |

Or one kilowatt-hour at a cost of 5 cents.

These instances show that good service can be rendered at a reasonable expense by existing devices, but I quite agree with Mr. Hadaway in his statement that we are still far removed from ideal conditions.

In a recent lecture on this subject Dr. Steinmetz went to the root of the whole matter, in discussing the possibilities of greatly reducing the cost of electricity by improving the station load-factor, aiming to get a steady and uniform load throughout the 24 hours of the day, when he said:

> When we have accomplished that, electric power will be much cheaper than anything else and then the end will come for gas and kerosene. And that time *will* come some time and we will probably see it.

Mr. Hadaway cites some favorable cases, such as first-class apartment houses in large cities, where steam heat, hot water, and electricity are supplied to tenants, and where, therefore, electric cooking may be performed economically provided only that the price of electricity is reasonable. It is nevertheless generally true that the cost of heating water by electricity for domestic purposes, at ordinary rates for current, presents an almost insuperable obstacle to its common use, excepting in a small way, such as for hot-water urns, coffee percolators, and similar table devices.

I believe with Mr. Hadaway that the field of industrial application will eventually be found equally if not more extensive and profitable than the domestic side. There are thousands of operations where heat is now applied to various parts of machines in a cumbersome and unhandy way by steam and gas where electric heat would be not only more cleanly and hygenic, but also more economical in the long run, on account of the especially favorable feature of being able to localize the heat where it is required, and other considerations covered by a variety of special conditions.

In regard to the heating of air in buildings, Mr. Hadaway has shown in a general way that the present cost of electricity when supplied from large generating stations makes extended applications prohibitively expensive. In a few special and isolated places it is applicable also for emergency cases where a maintenance or rise of temperature may be the means of saving valuable property, as in conservatories and greenhouses. where the value of these appliances is very evident.

**H. P. Ball:** The feature of the electric heating subject in which I am most interested is the design of the apparatus. Mr. Hadaway gives some comparative figures, stating that a circular gas burner will impart heat at a rate equivalent to 35 watts per superficial square inch, and electric heaters about one third of this amount, or about 12 watts to the square inch. He does not say how this gas burner was measured, but it might have been an annular surface, the surface of the flame, or the area of a circular disc; in any event, my experience would indicate that this rate can be exceeded. It is perfectly feasible by using modern materials, such as the new nickel-chromium metal and infusible insulating materials, to operate with watts running up as high as 20 on open stoves, and as high as 25 or even 30 on stoves which are used in connection with percolators or water heaters.

It appears that high temperature is the immediate field for electric heating devices, with the wide distribution of heat as something for the future, perhaps, but to-day the business to be had is in sad-irons and other devices where the heat is concentrated in small areas.

I call attention, therefore, to the absolute necessity of getting away from easily fusible materials, and adhering to the use of very high melting resistances, mica as the insulator, on account of its extreme thinness and high ground test, standing from 1000 to 1500 volts per mil of thickness, and metals, such as aluminum-bronze, which will not readily oxidize in the air at high temperatures.

As to the problem of heating rooms, the ideal arrangement would be the use of an exposed resistance conductor in the form of a thin but wide band, so as to have a maximum radiating surface, causing the conductor to operate at the lowest temperature; for it is a well known fact that if a conductor is surrounded with insulating material the conductor will run at a higher temperature for the same dissipation than if it were exposed in the open air.

In a sad-iron or water heater it is necessary to enclose the resistance, and in doing this it must be supplied with a maximum surface by using flat ribbon resistances. A material with a minimum thickness must also be used, such as mica, in order to get the heat out of the conductor into the thing we are trying to heat with the least possible thermal drop.

In a sad-iron the unit can be run at a very high current density on account of the specific capacity for heat of the surrounding iron; but in the water heater it must be restricted to lower densities, and care must be exercised to see that the surrounding material is of a minimum thickness, in order that the electrical energy and time taken in raising the temperature of the device to its working temperature may be the least possible.

**Max Loewenthal:** The author discusses the relative efficiency of steam, gas, and electricity and arrives at the almost self-evident conclusion that electrically generated heat is not so efficient for ordinary domestic or industrial operations as steam. He furthermore shows that the same is true when we compare electricity with gas for heating or cooking purposes. We have, however, many figures to prove that electrically heated appliances are as efficient, and frequently more efficient, than the same appliances heated by other means.

Take, for example, the case of an oven. The efficiency of an ordinary cooking-stove using solid fuel is only about 2 per cent, 12 per cent being wasted in obtaining a glowing fire, 70 per cent going up the chimney, and 16 per cent being radiated into the room. In a gas-stove, considering that the number of heat units obtainable from the gas at a certain price is but small compared with solid fuel, the ventilating current required for the operation alone consumes at least 80 per cent of the heat units obtained by burning the gas. In the case of an electrical oven more than 90 per cent of the heat energy can be utilized; and thus, although possibly 5 to 6 per cent only of the heat energy of the fuel is present in the electrical energy, 90 per cent of this, or 4.5 per cent of the whole energy actually goes into the food. Thus the electrical oven is practically twice as economical as any other oven, whether that oven is heated by solid fuel or by gas.

Furthermore, the comparative operating cost of electric and gas cooking depends upon two conditions; the relative rates for gas and electric heat units, and the relative heat efficiencies of gas and electric apparatus. A third quantity, the effect produced by the different rates and modes of heat applications in the two classes of utensils, may effect the efficiency slightly, but the existence of this effect is not yet verified. Starting with the heat of coal, which may be fairly estimated as 12,000 B.t.u. per pound, we compute the relative efficiency of the heat conversion as follows:

| Gas | Electricity |
|---|---|
| 1 pound of coal produces 5 cu. ft. gas. 5 cu. ft. of gas contain 3000 B.t.u. | 1 pound of coal produces 0.25 kw-hr. 0.25 kw-hr. = 853 B.t.u. |
| Efficiency of heat conversion is | Efficiency of heat conversion is |
| $\frac{3000}{12000} = 25$ per cent. | $\frac{853}{12000} = 7.1$ per cent. |

$$\frac{\text{Efficiency electrical heat conversion}}{\text{Efficiency gas heat conversion}} = 28.4 \text{ per cent.}$$

With manufacturing processes of equal cost per pound of coal converted, it is apparent that an electric heat unit must cost nearly four times as much as a gas heat unit, but with present processes the relative rates are:

| Gas | Electricity |
|---|---|
| $1.00 per 1000 cu. ft.<br>1 B.t.u. 0.000167 cents. | $0.10 per kw-hr.<br>1. B.t.u. 0.00293 cents. |

$$\frac{\text{Electric B.t.u. } 0.00293}{\text{Gas B.t.u. } 0.000167} = 17.5$$

It is known that the efficiency of electrical apparatus is about four times that of gas, and consequently, as the gas utensils require four times as many B.t.u., the above figure of 17.5 is reduced to 4.4. If, then, the rate for electricity is reduced to one-quarter of that assumed, or 2.5 cents per kilowatt-hour, this figure of 4.4 is changed to 1.1 and we have practically identical operating costs. This ratio has been borne out by numerous tests.

One of the most interesting figures contained in Mr. Hadaway's paper is the one relating to room heating.

> For room heating from 85 to 110 watts are practically equivalent to steam at low pressure condensed by one square foot of radiating surface, etc.

I may add that in practice we figure about 1.5 to 2 watts per cubic foot to be heated, under average conditions.

I do not believe that the heating element of the future will be altogether in the nature of a wire, a metallic paint, etc., but will probably be of a refractory character, such as a carbide, or a silicate of carbon. This will stand a red heat without apparent oxidation and is mechanically stronger than anything heretofore employed.

**Charles P. Steinmetz:** When using electric energy in producing heat energy for heating, cooking, baking, etc., we are confronted by the enormous handicap of the inefficiency of the thermodynamic engine. As electric power at the switchboard of a station we get only from 8 to 10 per cent of the energy of the fuel burned under the steam boilers, and have lost 90 per cent or more. When converting again this electric energy into heat energy, we can get only the same very small percentage of the heat energy of the fuel that is contained in the electric energy, and this greatly handicaps the use of electric energy in those cases where large amounts of heat are required, as in water heating. Therefore we always hear electric heating engineers refer to the use of gas or hot water or steam for the cases where large amounts of heat are required, as in water heating, or house heating, and reserving the use of electric heating for those applications where the heat capacity is small, as in cooking and baking, or for intermittent use, or where the convenience and cleanliness of electric heating outweigh other considerations. We look to future improvements in the production of electric power, and to improvements in the load-factor, to bring the cost of electric power down to such values as to compete in economy even in such fields as house warming, water heating, etc.

It is this statement of the inefficiency of electric heating, due to the inefficiency of the conversion of the heat energy of fuel into electric energy, that I desire to challenge. It is true that each kilowatt-hour of electric energy contains only a definite number of units of heat energy, 850 calories, and that the heat energy produced by the conversion of the electric energy into heat can therefore never exceed 850 calories of heat energy per kilowatt-hour, or about 8 to 10 per cent of the original heat energy of the fuel. The problem of electric heating is, however, not to produce heat energy from electric energy, but to raise the temperature of the air or some other objects by increasing the quantity of heat contained in them. This does not necessarily require producing the quantity of heat; it can be done by raising an existing quantity of heat to higher temperature, or higher heat level. For instance, to fill a vessel with water, the water could be produced by burning hydrogen gas in the air, but it would be more economical to fill the vessel with water by using the energy of the burning hydrogen to pump water from some lower level into the vessel. In the latter case, of the water in the vessel only a small part is produced; most of it is taken from an otherwise unavailable supply, a lower level.

In the thermodynamic engine, we supply a quantity of heat, at higher temperatures. Of this, a small part, say 10 per cent, is converted into mechanical energy, the remaining 90 per cent given off, "rejected", as heat at atmospheric temperature. The thermodynamic cycle, however, is reversible, and by performing it in the reverse direction, we could take the 90 per cent of heat at atmospheric temperature; that is, from the air, or the water supply, and by the conversion of the 10 per cent of mechanical energy into heat in the reversed cycle raise the other 90 per cent of heat from atmospheric to the higher temperature, and thus supply again the 100 per cent of heat at the same theoretical temperature at which they were supplied to the thermodynamic engine in the direct cycle. In this case we would supply at the higher temperature 10 times as much heat as corresponds to the consumed electric energy; but this heat is not produced from electric energy, 90 per cent has merely been raised from a lower level, lower temperature to a higher temperature. It is thus possible to supply, at the moderate temperature rise required by electric heating devices, many times more heat than the calories of heat energy corresponding to the consumed electric power, a larger quantity of heat even than the total number of units of heat energy of the fuel consumed in producing the electric energy, without infringing the law of conservation of energy. It is this possibility which Lord Kelvin referred to in the statement quoted in Mr. Hadaway's paper.

With a relatively moderate expenditure of electric power, such a thermodynamic engine could be operated between two temperatures, one above and one below atmospheric, and thus be used to heat the houses in winter or cool them in summer. Air, taken at atmospheric temperature, is heated by adiabatic compression; its heat is abstracted; then the air is expanded and thus cooled below atmospheric temperature, and heat supplied to it until atmospheric temperature is restored. Thus between compression and expansion, heat is given off above atmospheric temperature, and between expansion and compression heat is taken in below atmospheric temperature; that is, cold given off, and as the work done by the expansion supplies most of the work of compression, electric power has to supply only the differences; that is, a part of the energy representing the heating or cooling effect. Obviously, in summer the higher temperature, in winter the lower temperature, would be rejected by exhausting into the air and taking in a fresh volume of air at atmospheric temperature. Such a thermodynamic heating apparatus should be able, even with the present cost of electric power, to make the cost of electric heating comparable with that of direct heating by fuel.

**Townsend Wolcott** (by letter): In discussing Mr. Hadaway's paper, Dr. Steinmetz makes some statements about thermodynamics which, whatever he may have meant to say, are, as he has actually made them, misleading. First, assuming a thermodynamic engine with an efficiency of 10 per cent, as he does, the first great loss of temperature fall, and consequent dissipation of energy, is between the temperature of the fire and that of the boiler, if the apparatus be a steam engine; or between the temperature of combustion and the maximum allowable temperature of the cylinder, if it be a gas engine. In the steam engine, the temperature of the fire is at least 1000° fahr., while that of the boiler is less than 400°. It is not true, therefore, that, by reversing the cycle, the original temperature can be restored to the whole amount of heat, even theoretically; for the fall from fire to boiler temperature is a completely non-reversible process, and entirely outside of the reversible cyclic process. To be sure, if we were able to work down to absolute zero, all the energy of heat of any finite temperature would be available, and the drop between fire and boiler would be of no consequence; but, with a finite lower limit of temperature, such as Mr. Steinmetz uses, this drop is of the greatest importance. Secondly, if the expansion be carried below atmospheric temperature, as Mr. Steinmetz says it is, efficiency is sacrificed; it is precisely because the expansion is isothermal at atmospheric temperature, in the apparatus described by Lord Kelvin, that the efficiency is high.

Mr. Hadaway's quotations from Lord Kelvin's paper of more than half a century ago may be a little startling to those who are not familiar with thermodynamics; first, on account of a doubt as to whether the statements therein contained are quite true, in view of the fact that, upon superficial examination, there appears to be a regeneration of dissipated energy; secondly, because, if true, the principle does not appear to have been fully utilized. Upon investigation, however, all doubts are dispelled and the whole subject is illuminated. I have not seen the mathematical investigation published with the original paper, and to which Lord Kelvin refers in the passage quoted by Mr. Hadaway; but, as the numerical statements contained in the passage check satisfactorily, even when using the most modern values for the natural constants involved, it is, perhaps, of no great importance that I have not. Let us follow through the process described by Lord Kelvin, using, in the interest of simplicity and perspicuity, the ideal cylinder of Sadi Carnot, which is frictionless and has walls which can be made alternately perfect conductors and insulators of heat, and the ordinary pressure-volume diagram. The values of the natural constants will be taken from the fifth edition of Peabody's "Thermodynamics of the Steam Engine." First suppose that the piston be withdrawn to 0.82 of full stroke, and further suppose that, at this point, the cylinder contains exactly one pound mass of air, at the normal pressure of 2116.32 lb. per square foot, which we will designate by $p_1$. So far, no work has been done. Now suppose the intake valve closed and the piston drawn out to full stroke, the temperature of the air in the cylinder being maintained constant by conduction through the walls of the cylinder. At the end of the stroke, the pressure will be $0.82 p_1 = 1735.382$ lb. per square foot $= p_2$ The volume at $p_1$ we will call $v_1$ and at $p_2$

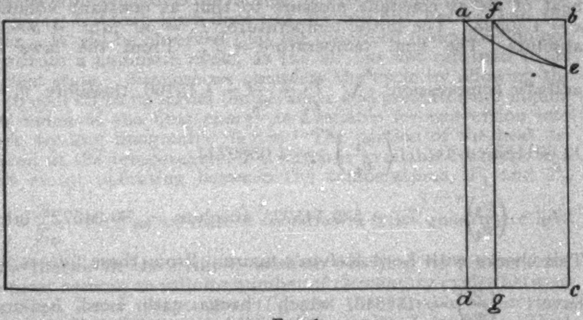

FIG. 1

we will call $v_2$. $v_1 = 12.84375$ cu. ft., $v_2 = 15.66311$ cu. ft. The work of isothermal expansion is

$W_i = p_1 v_1 \log_e \frac{v_2}{v_1} = 5394.186$ ft-lb., and is represented on the diagram by the area, *a, e, c, d.* The total work required to move the piston from $p_1$ to $p_2$ against the atmospheric pressure is $p_1\ (v_2 - v_1) = 5966.668$ ft-lb., represented in the diagram by the area *a, b, c, d.* The difference of these areas; that is, the area, *a, b, e,* represents the external work supplied, $W_0 =$ 572.482 ft-lb. The cylinder is now insulated and the piston allowed to go back until the pressure in the cylinder is again $p_1$; the volume at this point $= v_3$. The compression is adiabatic, and the temperature, of course rises. Assume the absolute zero as $-459.5°$ fahr., the specific heat of air at constant pressure as 0.2375, the mechanical equivalent of heat as 778 ft-lb. From these values we obtain that for the ratio of the specific heat of air at constant pressure to that at constant volume, $\kappa = 1.40593$. The initial temperature, $T_1 = 50°$ fahr. $= 509.5°$ absolute. The final temperature $= T_2$. From the laws of adibatic compression, $\sqrt[\kappa]{\frac{p_1}{p_2}} = \frac{v_2}{v_3} = 1.15160$. therefore, $v_3 =$ 13.601183 cu. ft.; $\left(\frac{v_2}{v_3}\right)^{\kappa - 1} = 1.0589711$.

$$T_2 = \left(\frac{v_2}{v_3}\right)^{\kappa - 1} T_1 = 539.54572° \text{ absolute} = 80.04572° \text{ fahr.}$$

This checks with Lord Kelvin's figure. From these figures we have $1 - \left(\frac{v_3}{v_2}\right) = .131643$, which checks with Lord Kelvin's statement of the amount of compression. The work of adiabatic compression is $W_a = \frac{p_1 v_3}{\kappa - 1} \left(1 - \frac{T_1}{T_2}\right) = 3948.718$ ft-lb.: this is represented on the diagram by the area, *f, e, c, g.* The work which the atmosphere is capable of doing on the compression stroke is represented on the diagram by the area, *f, b, c, g,* and equals 4363.721 ft-lb. The difference between this and the work of compression = 415.003 ft-lb., and is represented on the diagram by the area, *f, b, e.* As this work may be, at least theoretically, stored so as to be available for use in the next expansion, it is only the difference between it and the work originally required to pull the piston out which is permanently absorbed. This difference, represented on the diagram by the area, *a, f, e,* equals 157.479 ft-lb. The equivalent in work of the heat required to raise one pound of air from $T_1$ to $T_2$, and at the same time expand it from $v_1$ to $v_2$; that is, to heat it at constant pressure, is 5551.698 ft-lb. As this is a little more than 35 times the work absorbed, Lord Kelvin's numerical results check completely. However, the casual reader of Lord Kelvin's paper finishes with a more or less distinct idea that some dissipated energy has been reclaimed; or, at least that the Bell-Coleman refrigerating apparatus is more economical than some others. I do not mean to intimate that Lord Kelvin had any such idea, but simply that the ordinary reader is inclined toward that opinion, and it is to make the truth regarding this matter clear that I have gone through the foregoing calculation in so much detail. The regeneration of dissipated energy, or the flow of heat from a cooler to a warmer body, without an equivalent flow of heat from a warmer to a cooler body, is contrary to the second law of thermodynamics. The number of proposed machines intended to operate in defiance of this law would probably make a respectable second to the number of proposed perpetual motion machines; but one kind does not operate any better than the other. It will be observed that the described operations do not constitute a complete cycle, as the air has not returned to its original state. Suppose we complete the cycle by allowing the air to cool off to its initial temperature and pressure, and inquire how much of the heat energy is available for conversion into work, by any imaginable device. The portion of the heat delivered at the temperature, $T_2$, which is available for work in a heat motor operating between the temperatures, $T_1$ and $T_2$, is $1 - \frac{T_1}{T_2}$. But, as we cannot withdraw a finite quantity of heat from the air in the cylinder without lowering its temperature, we must assume an infinite number of elementary cycles between the fixed lower temperature $T_1$, and the variable upper temperature, $T$, and integrate between the limits, $T_1$ and $T_2$. Thus, allowing for the specific heat of air.

$$\text{Available energy} = 0.2375 \int_{T_1}^{T_2} \left(1 - \frac{T_1}{T}\right) d\,T =$$

$$.2375 \left((T_2 - T_1) - T_1 \log_e \frac{T_2}{T_1}\right) = 0.2024569 \text{ B.t.u.} = 157.511 \text{ ft-lb.}$$

which is pretty accurately equal to the absorbed work, as calculated in the foregoing. Had more places of figures been employed in the calculations, the agreement would have been closer. We see from this investigation that no dissipated energy has been regenerated or recovered, and that the only energy which can be, even theoretically, recovered from the cycle is just what is put in. An examination of the records of tests of ice machines in Professor Peabody's book shows that the Bell-

Coleman apparatus is no more economical than apparatus using ammonia and other volatile liquids, but this does not in any way invalidate Mr. Hadaway's contention that the heating of houses by electric motors and Kelvin apparatus would be more economical than by rheostats, even allowing for the inevitable losses in a practical machine. If the limits of the temperature range were extended, so as to boil water or cook, the economy would diminish and, ultimately, disappear altogether.

**W. S. Hadaway, Jr.:** Concerning some of the criticisms of the paper: it has been my effort to make it very conservative. The logical way to look at the matter is to conserve the fuel supply so far as it can be made to go. From a business standpoint, and it is really the business standpoint that determines the engineering features, it has been shown conclusively that a demand for electric heating apparatus has been created which must be met. It has become in many ways not so much a question of what the efficiency is as of results attained.

It has been thought desirable in connection with the practical side of the problem to point out some of the difficult questions yet to be solved. I thank Dr. Steinmetz for elaborating the Kelvin method of securing heat in large quantities at low temperature.

In the construction of apparatus the one important factor which remains to be solved at present is the question of heat insulation. If we were building ships in which we had to figure a certain percentage of tonnage capacity set aside for pumps to keep the ship afloat, we would be in relatively the same position as is the manufacturer of electric heating devices to-day so far as energy inputs are concerned. We have no practical method of confining heat at high temperatures.

I was asked a question as to how the statement that the gas burner corresponded to something like 35 watts per square inch was derived. That statement is based on laboratory work, in which gas stoves of ordinary construction with annular burners and with outside dimensions of approximately 6 in. are compared with an electric heater upon which a vessel of the same size was used on the two devices. It should be added, however, that the limitation of the watts per square inch is not necessarily as low as 12 watts, because on low voltages apparatus has been successfully used up to as high as 40 watts per square inch. The voltage situation, however, particularly on 220 volts, is a difficult proposition to handle, because apparatus built for that voltage has one fourth the resistance cross-section of apparatus built for 110 volts, and the electrical insulation has also to be somewhat increased.

The logical development in voltages is towards a decrease rather than an increase in the same way that the logical development of quantitative work in heating is the centralization of all the heating values at one point and the distribution of them over short distances to secure the highest fuel efficiencies in combination with the advantages which the electric heating devices give.

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# THE LOG OF THE NEW HAVEN ELECTRIFICATION

BY W. S. MURRAY

## SYNOPSIS OF PAPER

**Introductory**

1. Object of paper.
2. Value of mistake.
3. Value of ignorance.
4. Facts—necessary to stable conclusions.
5. Effect of experience on decision.
6. Relation of steam versus electric traction.
7. The new chain—its old links.
8. The public.

**Major Faults**

1. Power house.
2. Insulation.
3. Circuit-breakers.
4. Line.
5. Locomotives.

**Minor Faults**

1. Generator burn-outs.
2. Distribution.
    *a.* Multiple-track circuits.
    *b.* Independent track circuits.
3. Contact wire.
4. Hard spots.
    *a.* Hangers; *b.* section breaks *c,* deflectors.
5. Signal wires.
6. Locomotive current collectors.

**Log of Operation**

1. Electric passenger service.
2. Electricity versus steam.
3. Train-minute delays; *a,* table; *b,* chart.
4. Serious failures—over 300 train-minutes.
5. Engine repairs—*a.* Table showing engines in shop.
6. Engine capacity—*a.* Table showing trailing loads in excess of guarantees.
7. Engine - mileage — electricity and steam compared.

**The Electrification in Relation to Matters Other Than Traction**

1. Telegraphs and telephones.
2. Public safety.
3. Foreign wires.

**Commentary**

1. Lightning protection.
2. Grounds.
3. Tell-tales.
4. Train heating and lighting.
5. Fatalities.
6. Single- versus double-catenary construction.
7. Cross-catenary versus bridge bents.
8. Single-phase operation.

**Conclusion**

1. Alternating current and the engineer.

New York, New Haven and Hartford Railroad Company.

# THE LOG OF THE NEW HAVEN ELECTRIFICATION

BY W. S. MURRAY

The object of this paper is to bring the actual operation of the New Haven single-phase electrification as closely as possible to those who are truly interested in its merits and faults. If the writer can feel that this object has been accomplished, the reward for the effort will be sufficient.

In advance of freely opening up the subject without mental reservation, it may be well to say that he is not unmindful of the adverse construction and criticism that will be placed by some upon the facts he intends to present. Having carefully weighed this, however, he has concluded that it should not be permitted to stand in the way of, or militate against, the sounder and analytical judgment of those intent upon a fair consideration of the facts as they exist.

The first intention was to make the subject of this paper " The Errors Made in the Electrification of the New Haven System ", but realizing what capital such an " admission " would make for those few who are inclined not to be fair-minded on this important matter, the title has been changed, and the body of the paper built upon a description of the faults, major and minor, that have been made, and their effect, by log-sheet reference, upon operation. After all, the citation of " how not to do it " is far more valuable than " how to do it ". It may be at some sacrifice of pride to discuss one's errors, yet there is something so valuable in the exposition of an error that this, in itself, is ample compensation for its acknowledgment. There seems to be, too, something altruistic about a mistake or " wrong "; for in its death there is born a " right ", and one can never really get on intimate terms with his mistake until its rightful complement has been substituted. After a railroad has changed from a steam to an electric schedule, the natural question immediately follows: "Is it a success?" The answer to this question involves almost an infinity of analytical judgment. Electrical engineers have no greater professional or moral responsibility before them than the presentation of all available data, in which will be included information of pertinent application in the solution of the vast electrification problems of to-day. To those entrusted with the responsibility of such decisions is due every possible help and light. Engineering conclusions are based on 5 per cent. theory and 95 per cent. practice; practice being made up of experience and an acceptance of existing allied conditions. We want nothing unless we know all about it before it is ours. If we are wise, we should not be so particular about its merits as its demerits. Perfection cannot exist. This applies to electrification as to other things.

The duty assigned to the engineers of the New Haven railroad was to provide for the electrical operation of its trains. At the early period of April 1, 1905, when we settled down to this responsible task, the data in the field, upon which to base real conclusions, were about 5 per cent, in comparison with the experience now available. If "Ignorance maketh the brave", I can only say that I am more than thankful we were so ignorant at the outset. I do not believe that this remark will need any explanation here. Could we have read the history of our errors, rather than have made them, I question whether we would have had the temerity—though I confess our convictions would have been the same—to ask the president of the New York, New Haven & Hartford Railroad Company to put up with the criticism, abuse, and unfair remarks that have been made by those ignorant of the facts, and by others who, perversely, were intent upon their own selfish, narrow course with manifested abandonment of all purposes to acquaint themselves with the nature, the scope, and the possibilities which lay easily within their knowledge, merely by the asking. To-day, I am thankful to say, this negative attitude is giving away to the alarm made manifest by undisputed facts, which demand their own recognition. I have no personal desire to make any other engineer think as I do. If he sees the facts as I see them, then we will vote alike. To those who may be interested in my conclusion in regard to the New Haven Railroad electrification, I can simply say that, if I were in favor of its use three years ago, now, standing on the more stable ground of experience, particularly in regard to the department of faults, I am doubly in favor of it to-day. I shall, of course, be interested in those who share this opinion after reading this paper, but I shall be doubly interested in them if their conclusion has not, in the slightest degree, been influenced by my own, but has been formed entirely upon the contemplation of the faults severally cited. And, let me quickly add, I shall be equally interested in those who honestly disagree with this opinion.

Unlike steam traction, where the number of links in the delay chain is but one, electric traction has its delay chain composed of three links; namely, the power house, line, and locomotive. A failure in any one of these links may produce train delay or delays. Measured by the degree of their seriousness, these links, in the order of their effect on delays, may be mentioned in the order given. This is, of course, immediately apparent, in that the power house affects all operation; the line, a considerable portion of the trackage, involving, possibly, several trains; and the locomotive is usually confined to its individual troubles, only infrequently affecting following trains. This order naturally has application to all forms of electrification, direct current, single phase, or polyphase.

In the conception of the form of power house, line, and locomotive to be used in the New Haven system, ignorance and lack of experience led those pertinently interested in its success to believe that while the chain of power generation, and its transmission and utilization for traction, was of a new character, its links, however, were made up of principles long recognized and reliable. They were right in this conclusion, except that it did not include certain phenomena which could not have been anticipated, due to the combination of these old principles in the form of this new chain. For example, there was nothing particularly disturbing about an 11,000-volt 25-cycle, three-phase power house, from which was to be taken most of the power from one of the phases generated; or of a 300-ft., 11,000-volt, single-phase transmission line, from the terminals of which the same voltage was to be distributed, east and west, along the right-of-way of a railroad; or of a locomotive with a transformer installed upon it to take 11,000 volts and step it down to 600 volts to supply 300-volt single-phase railway motors. Power houses of this character have been designed the world over, except perhaps that single-phase current in the amount to be utilized had not been used elsewhere. Transmission lines of 60,000 volts had been in constant use. And, except that there was a moving contact in connection with the current that was to go to the step-down transformers on the locomotives, transformers of many times the capacity and voltage were in universal use. The single-phase motor, indeed, may be said to have been new so far as the size required for the New Haven service is concerned, but tests made upon smaller units demonstrated beyond peradventure its tractive qualities and showed its characteristic curves to be closely similar to those of its prototype, the direct-current motor. This reasoning, in close consideration of each class of apparatus, *per se*, has proved itself correct, and such irregularities as have existed in the initial electric service which the New Haven road offered to the public, while deserving the condemnation which the public can unfailingly offer, have been due to the ramification of a series of faults that have developed entirely outside the zone of previous experience. The delays (and public criticisms of them) have followed even to this late day, when the electric service is far better than the steam service it has replaced. It has occurred to me that certain engineers, who are unbelievers in the single-phase system, may interpret this paper as an apology. To them I would say, as I do to the public, it is an apology for having delayed any of their appointments. To others, it is needless to add that the citation of these troubles is given in the hope that they will, as they easily can, avoid them in the future.

## THE SERIOUS FAULTS

*Power house.* The electric power supply for the New Haven road is derived from four 11,000-volt steam turbine generators. three of which have an electric capacity of 3750 kilovolt-amperes single phase; the fourth unit consisting of a 6,000 kilovolt-ampere, three-phase generator, which can also supply single-phase current to the system.

Although the generators as originally designed were made exceptionally strong, and particular attention paid to their insulation, due to the necessity of grounding one phase, it was found that the utilization of so much single-phase current from a three-phase star-wound generator produced a stray magnetic field completely out of the path of normal lamination. As a result it was impossible to develop for continued operation more than 66 per cent. of the normal rating of the generators. Overloads of any character produced abnormally rapid heating, making such operation dangerous, although the generators were guaranteed to carry 50% overload for two hours, and 100% overload for two minutes, in order to meet the sudden drafts of currents required for a schedule such as exists on the New Haven road. Indeed, at the very start the actual drafts of current showed that the generators must meet imperatively the guarantees as to normal and overload capacities if the electrification were to be successful. These, then, were the power house conditions that confronted the New Haven road on beginning the work of propelling alternating-current trains. The power house being the heart of an electric system, to add more would be to say less in describing a critical situation.

I trust it is not to be my pleasure to meet the prophet, who says, "This could have been anticipated." Suffice it to say that after three unsuccessful attempts at complete correction, each, however, affording some constructive results—months being absorbed in the dismantling and readjusting of the parts of these generators—the final attempt was successful and the generators are to-day operating in the power house, fulfiling the guarantees mentioned previously. But this last mentioned fact is insignificant when compared with the valuable information that has been derived, which will permit all other generators to be manufactured without the fault described.

*Line insulation*. The years of experience which we have had in the study of insulating various voltages led to what was considered a very conservative insulation in the various parts of the line. Messenger cables had to be insulated from the intermediate trusses and at their anchor-bridge termini. The trolley copper conductor was suspended from the messengers and had to be insulated at points where it entered the oil switches on the anchor bridges. Trolley wires had to be insulated from each other at section breaks. On curves, both messengers and trolley wires had to be strained over the center of the tracks through the agency of pull-off posts at the side of the tracks, the pull-off wire being insulated between tracks and the pull-off column itself. Feeder wires had to be insulated from their supporting cross-arms and at points where they pass under highway bridges. None of these problems in insulation had the appearance of an especial character and, indeed, did the road-bed provide traffic only for electric trains, the problem would have been simplicity itself. A pressure of 11,000 volts being the prevailing dielectric strain, the problem was to provide sufficient insulation at all the points mentioned above.

Of the effect of steam locomotive discharges upon insulators, there was no initiative by which to be guided, and it became necessary to decide upon the factors of insulation that would be required. It was thought that ample provision had been made: it proved otherwise. Experience has proved that, in places, just double the amount is required. It was quickly noted that the greatest number of insulator failures occurred wherever the insulation was subject to the direct blast of the steam locomotive. To correct the difficulty, therefore, it was found necessary to double up on anchor insulators. The intermediate messenger insulators proved adequate and it was not found necessary to increase the impregnated stick insulation between trolley wires at curves, but wood stick insulators had to be added in series with the moulded material insulator between the pull-off wire and pull-off post. The original insulators on the anchor-bridge switches were made of moulded material and for them was substituted porcelain. It was not necessary to change the feeder insulators on the catenary bridge struts. While very little trouble has been experienced with the form of insulation used for supporting the feeders under highway bridges, it is anticipated that trouble will follow if this is not changed. The present form consists of the corrugated spool-type insulator, for which there will be substituted a regular porcelain double-petticoat insulator.

To-day, instead of line failures being the rule, they have become the exception.

*Circuit-breakers*. The momentary energy involved in a short-circuit produced upon a line fed by high-power, high-speed turbines is very great. Under the sub-title "*Power house*" it was stated that the generators were operating under their guaranteed capacities. Internal heating, due to stray magnetic field, was the cause of the generators failing to meet their designed capacity. This heating was completely cured by the simple addition of a short-circuited winding surrounding the rotating member of the generator, similar to that used in the well-known squirrel-cage type of induction-motor rotors. It is interesting to note here, however, that while the heating is entirely eliminated by this short-circuited winding, its effect on the occasion of a short-circuit is to allow more current to flow. This tendency, however, is controlled by a method later to be described. In the New Haven system, as the current from the power house was fed directly to the line and from there to the locomotives without transformation of voltage by transformers, the inductive element to counteract the surging current was practically negligible; under these conditions there resulted short-circuits which no circuit-breaker apparatus then designed could be relied upon to take care of.

Here it is expedient to point out the very marked difference in operating conditions between circuit-breakers used on a system that is grounded and one that is not. In either case, it is, of course, good practice to ground the frames of all circuit-breaker apparatus. In the case of the grounded system, this virtually brings one terminal of the generating system directly to the frame of the circuit-breaker; with the other terminal of the system connected to the jaws (contactors) of the breaker, it is readily seen that on the occasion of a heavy current surge, due to short-circuit, should the arc extend itself through the walls of the oil tank (wherein the circuit is broken), this would be a direct leakage to ground, establishing a short-circuit around (or in shunt) to the circuit-breaker jaws, which action, of course, renders the circuit-breaker useless, and subjects it to the damaging effect of the arcing locally produced until interrupted by another circuit-breaker in series with the circuit. On the other hand, where the system is not grounded, even should the walls of a circuit-breaker be broken down, as explained above, there would be no electrical connection (unless the neutral be grounded) between the circuit-breaker frame and the generator, and thus no return path for the current. I desire to draw particular attention to this point, for while the circuit-breakers used in our case open short-circuits, since the current surges have been practically eliminated, I believe that the lining of the oil tanks should have an especially high insulation factor on grounded systems.

The failure of circuit-breakers, either in the power house or on the line, naturally produced train delays of large or small magnitude. It was difficult to believe that these large circuit-breakers were incapable of taking care of the short-circuits, and some time was wasted in thinking this way. Therefore, we reluctantly but surely arrived at the conclusion that the conditions would have to be changed.

The remedy was simple. Instead of feeding the main line

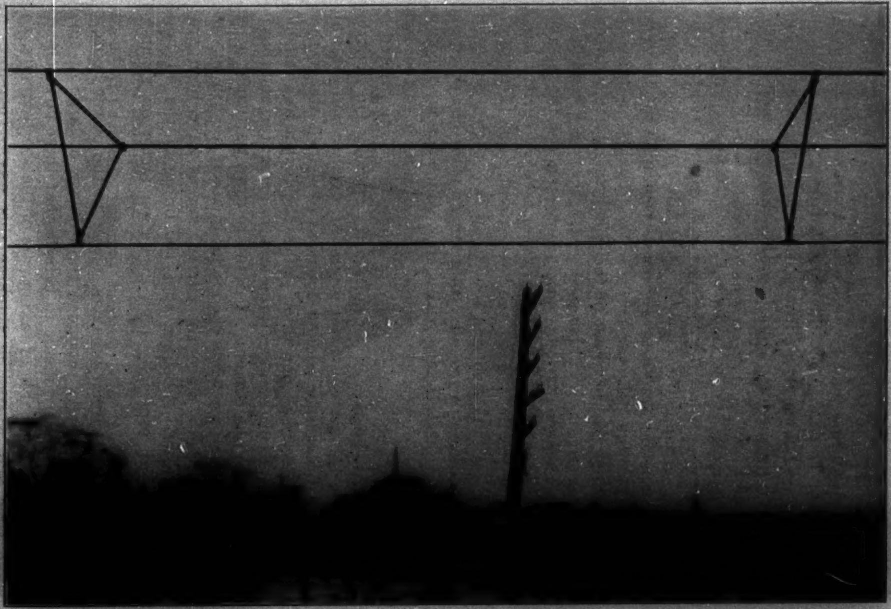

Fig. 1—Original copper trolley suspension

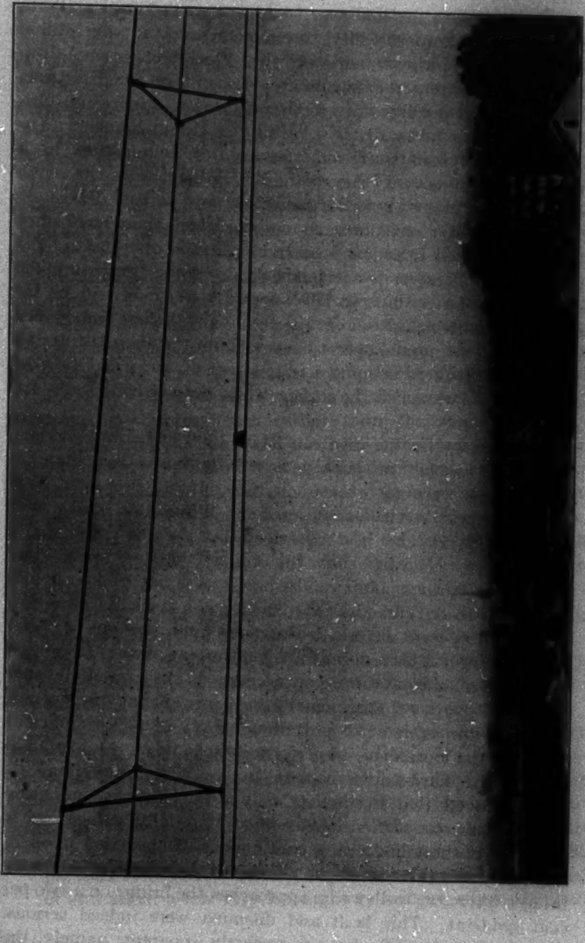

FIG. 2—Auxiliary steel contact wire suspended from original copper trolley wire

with a direct transmission straight from the power house busbars to the trolleys directly opposite the power house, the current was fed into the line over feeders connected to it at Portchester and Stamford. By the introduction of this ohmic resistance, amounting to not more than 2 per cent. normal drop on the system, we were immediately released from the disastrous effect of short-circuits on our circuit-breaker apparatus. Instead of losing as many as a half dozen circuit-breakers in a day, not that many were reported out of commission in a month, and, of course, they were not damaged to the same extent as the others, nor did they cause any serious delays.

For the feeder resistance, above described, there have since been substituted impedance coils, installed in the leads of the generators. These coils act as shock absorbers, protecting the generators. Later, it is to be expected that there will be installed a circuit-breaker across the terminals of these impedance coils, which, for normal operation, will shunt the current through them, the breakers opening under stress of abnormal flow of current and automatically closing when normal conditions are restored.

*Trolley wire.* In the month of May, 1908, it became evident to us that within at least one month from that date, if some change were not effected in the contact wire, the New Haven electric service would cease. While this truth was so plain, it may be best described by the fact that daily reports were showing that the copper trolley wire was breaking at various points; and where it was not broken it had become so badly kinked at the hanger points that it was impossible to operate electric locomotives upon the line without serious arcing. This resulted in violent surging on the locomotive transformers, and, at times, on account of the extremely poor contact of overhead shoes on the line, in reducing the voltage to such a low value as to prevent a supply of power sufficient to enable the locomotive to perform its schedule. An examination of the hard-drawn copper trolley wire throughout its length proved that even after only a few months' operation upon it, its cross-section had been so materially reduced as to point to its short life with a continuance of operation upon it. Especially was this true in the vicinity of the many low highway bridges where the trolley wire approaches the bridge on a two per cent gradient. This fault and dilemma were indeed serious. The cause of the difficulty was perfectly apparent; namely, the hard spots in the line which existed at the hanger points.

Many suggestions were offered. None of them, however, offered the speedy installation that was paramount. Mr. McHenry, vice-president of the New York, New Haven & Hartford Railroad Company, made the suggestion that an auxiliary wire be suspended from the present copper wire (Fig. 2) by clips at its midpoint between the hangers, and followed it with the suggestion that this auxiliary wire be made of steel, of the same cross-section as the 0000 grooved hard-drawn copper wire above it. It took two weeks for the manufacturer to draw two miles of this wire. It was installed immediately upon its receipt on the main line between Port Chester and Harrison. On the night of its completed erection a special seven-car train with two locomotives was operated upon it for several hours. Previously to the installation of the steel wire there had been installed a section of hard alloyed wire suspended in a manner similar to that of the steel. The electric train was operated upon them both, officials from both the railroad company and the contracting company being on hand to note their comparative merits. It was the consensus of opinion that there was less sparking on the hard wire, and the general tendency was towards adopting that rather than the steel. Though admitting that the operation was better, the steel seemed to be of an entirely satisfactory commercial nature, and all present finally concurred in this conclusion. It is undeniably true that hard alloyed wire would, from a purely operative point of view, be the better of the two, and yet the commercial aspect, which would naturally include its cost, had to be considered, particularly in reference to so large an immediate order as one involving 100 miles of single-phase electric trackage. Again it is important to note that the steel, besides having the advantage of being a cheaper, harder, and stiffer wire, also possesses a lower coefficient of expansion and higher elastic limit, especially valuable characteristics for the service desired. We found that we would be considerably delayed in the delivery of the steel, but an immediate order of 20 miles, followed by another for 40, was placed, and as much hard alloyed wire put up as could be obtained between the date of the conclusion to use the auxiliary wire and the final arrival of the first shipment of steel. The auxiliary wire construction on the main line, as described, prevails throughout the whole system, except at the approaches of and under a few very low highway bridges, where the contact system consists of two wires strung in the same horizontal plane.

The New Haven trains have been operating now on the auxiliary wire for several months, and absolutely no kinking has been noted at the hanger points, with the attendant result of a smooth and almost sparkless overhead contact.

*Locomotives*. There were originally purchased 35 locomotives, which was considered an adequate number to take care of the New Haven passenger service. These locomotives, considered *per se*, were rated on a half-unit basis. That is to say, the half unit was designed to handle about 75 per cent. of our trains, the remaining 25 per cent. to be handled by two units. Only a short experience in commercial operation revealed two important facts: the first one of a very encouraging nature; the second, decidedly otherwise. The first was the proof that the two main parts of the locomotive; namely, the transformer and motors, had sufficient capacity to more than handle the manufacturer's guarantees. The second was the discovery that many of the auxiliary electrical and mechanical parts of the locomotive equipment were not of equivalent capacity. The strength of the chain being measured always by its weakest link, it was immediately seen that the locomotives would be able to handle trailing loads in excess of their guarantees if the auxiliary parts were made of sufficient capacity to furnish the necessary current for the overload conditions. It was simultaneously apparent that more locomotives would be required to provide for an increase of train service and the reduction of time schedule, and an order was promptly placed for six additional ones; before accepting their design, however, a careful survey was made of all the component parts of the locomotives at hand, in order to determine the changes necessary to be incorporated in the six new engines. To accomplish this it was found necessary to make a number of electrical and mechanical changes, the nature of which is apparent in the following tabulation:

| MECHANICAL | ELECTRICAL |
|---|---|
| *Air Reservoir System*. Revised. | *Ammeters*. Revised. |
| | *Battery*. Charging relay installed. |
| | *Blowers*. Commutator slotted |
| | Waste rear bearing. |
| *Boilers*. Installed. | Armature laminations ground. |
| | Bearing raised above center. |
| | Motor winding revised. |

### MECHANICAL

Stack hood removed.

*Bell Rope.* Installed.

*Blowers.* New design installed.

Guide on present damper rod.

Extra guard on shutter.

*Bolster.* Reinforced on truck.

*Brakes.* New release spring.

Cylinder leads lengthened.

Check nut on adjuster.

*Compressor.* Drip pans installed.

Exhaust pipe installed.

Air-cooled cylinder head.

*Check-valve.* In whistle pipe

*Gauge.* On oil tank.

### ELECTRICAL

*Controller.* Bushing riveted.
Shoe and trolley switch installed.
*Circuit-breaker.* Fused.
Tank bolt secured.
New type installed.
*Compressor.* Commutator slotted.
Armature laminations ground.
New governor installed.
Bearing raised above center.
*Cut-out Boxes.* New drums.
*Fuse.* In alternating-current heater circuit.
New auxiliary fuse box (wooden.)
Auxiliary motors separately fused.
*Grounding switch.* Installed.
Control revised.
Shutter in cover.
*Heater switch.* Shield installed.
*Heater bus-bar line.* Reinsulated.
Couplers repaired.
*Headlight.* Adjusted properly.
Porcelain switch installed.
*Motors.* Holders reinsulated.
New cross-connecting leads.
Housing asbestos lined.
Linen tape on commutator end.
Side commutator covers perforated.
Perforated S. I. commutator covers.
Field clamp bolt secured.
*Motor-generator.* New switch.
*Preventive coils.* Revised.
Supporting frame revised.
*Direct-current relay.* Connection to "—S" switch.
Washer installed.
*Resistance.* Insulated.
Capacity increased.
Connected ahead of motor.
*Switch group.* Revised shunts,
Revised studs,
Revised arc shields,
Copper reverse switches,
One-turn blowout coils,
Air ports enlarged.

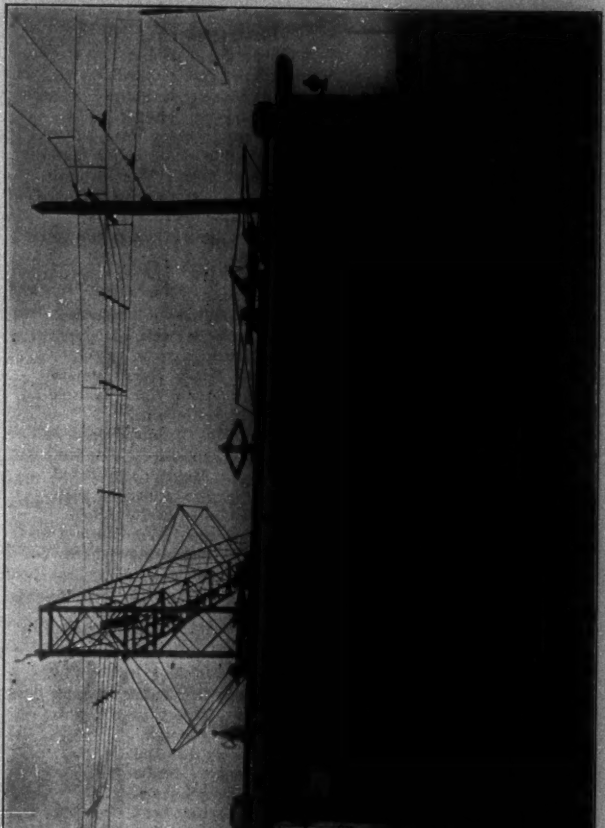

Fig. 3—Locomotive without pony trucks

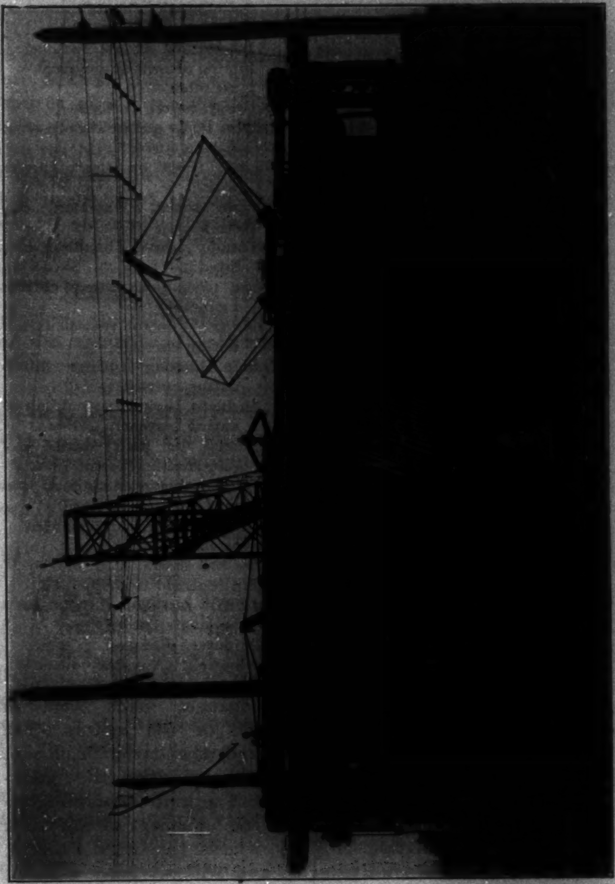

FIG. 4—Locomotive with pony trucks

MECHANICAL

On steam line.

*Journal-box.* Revised gibbs.

*Quill-plate.* Washers installed.

*Running-board.* On roof.

*Semi-elliptic springs.* 14 leaf.

*Safety-valve.* On control resistance

*Safety-chain.* Made heavier.

*Torque rods.* Heavy installed.

*Uncoupling lever.* Revised.

*Pony wheels.* Installed.

*Valve.* On oil line to boiler.

ELECTRICAL

Alternating current frames insulated.
Cylinder aligning set-screws.
Reinforcing wooden strip.
Interlocked reverse switches.
Fitting alternating current switches.
Group covers perforated.
New B. O. coil pole piece alternating current.
*Switch.* Block on direct current case.
Main switch, connection modified.
Canopy switch handles insulated.
*Shunt remounted.* Direct current ammeter.
*Trolleys.* Control revised (alternating current).
Side bearing springs (alternating current).
Insulate back cross-rod (alternating current).
Shield for high tension lead (alternating current).
Spring shortened (direct current.)
Insulator filled and painted.
*Temperature Indicators.*
*Third-rail shoes.* M. I. bracket.
Pin replaced by bolt.
Jumper installed.
Shoe levers cut off.
*Fuse boxes*—Refitted.
*Wattmeter.* (Auxiliary) installed.

The most important electrical changes made were in the switch-groups and brush-holders of the motors. The former lacked carrying capacity and the latter sufficient insulation. To these shortcomings were due the greatest number of our first train delays. The most important mechanical changes necessary were the reinforcement of the truck bolsters and installation of pony wheels (see Figs. 4 and 3, respectively, for locomotives with and without pony wheels). The especial reference to these electrical and mechanical changes must not be construed as diminishing in any way the force of necessity of the others, as they were all considered absolutely necessary in order to preserve a low cost of electrical and mechanical maintenance.

With the exception of the installation of pony trucks, the six new electric locomotives arrived within five months of the date of their order. In their design were included all of the changes above specified. To be noted here is the marked value of the spring type of armature and field suspension begun with the New Haven locomotive motors, thus making flexible the entire motor suspension. Indications already predict that this arrangement in combination with the pony trucks will reduce materially the track and locomotive maintenance and repairs. To-day the reconstruction, as above described, has been effected on over 90 per cent. of our locomotives.

This last and serious fault with which we had to contend completes the major difficulties that were constantly threatening the regularity of electric service.

It seems to be the time and place, here, to draw attention to a point in design concerning the New Haven locomotives that has been so persistently misrepresented by those who seem to have been ignorant of the facts. The specifications upon which the locomotive units were purchased, as stated hereafter, were that each unit would handle a normal trailing load of 200 tons. The writer, by careful measurement of the weights of all the trains (trailing loads) in the New Haven service, found that they averaged 212 tons. It seemed good engineering if 75 per cent. of the service could be handled by locomotives rated upon a basis of 200 tons trailing load, that that would be the correct locomotive unit size; using two units for the remaining 25 per cent. of the trains. To-day, three years after this decision, we find that 73 per cent. of our trains can be handled with single units, 27 per cent. requiring two units. The percentage is slightly different from the original, as the service is slightly heavier.

Coincident with the use of the first double-unit locomotive trains there was started a rumor that the New Haven locomotives did not have the capacity for which they were designed. To dispel this idea forever, I judge the best argument is to refer to Table X, wherein are stated the trains whose weights were in excess of the trailing loads which the locomotives were designed to carry.

I trust that the above clears up any erroneous ideas con-

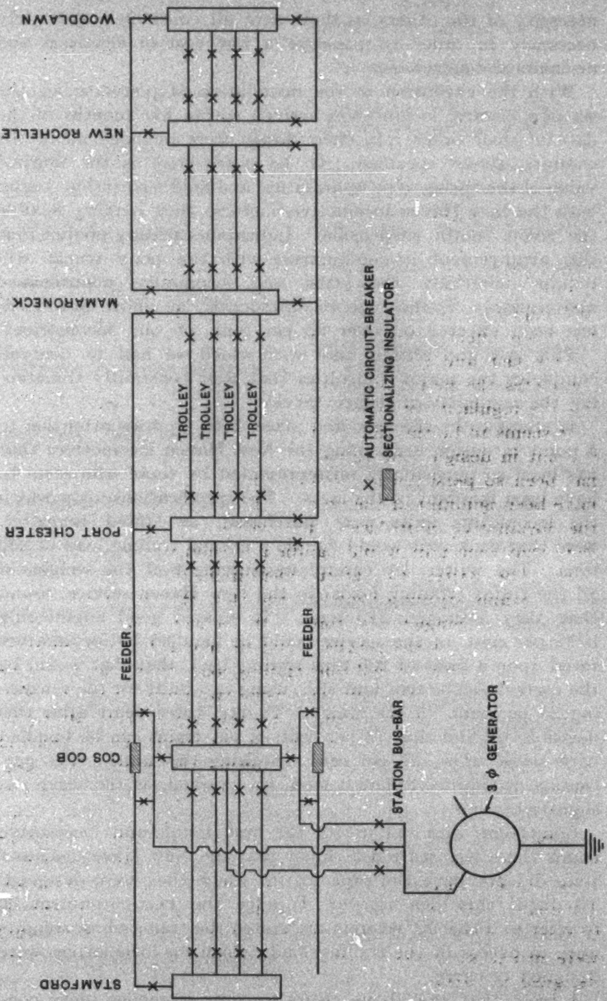
WOODLAWN
NEW ROCHELLE
MAMARONECK
PORT CHESTER
COS COB
STAMFORD
TROLLEY
TROLLEY
TROLLEY
TROLLEY
FEEDER
FEEDER
STATION BUS-BAR
3 φ GENERATOR
× AUTOMATIC CIRCUIT-BREAKER
▨ SECTIONALIZING INSULATOR

Fig. 5—**Independent track circuits**

cerning the capacity of the New Haven locomotives, and will justify the future double-unit trains entering and leaving the Grand Central Station.

Recapitulating, I believe my brother engineers will agree that with the coincident difficulties described in our power house, line, circuit-breakers, trolley wire, and locomotives, the work of instituting electric service was not exactly laid over a bed of roses. These are the serious faults the system possessed and the description of our method of elimination of them that I am glad to be able now to place before you. We cannot blame the public for making the complaints they have against the New York, New Haven & Hartford Railroad Company's electric service, for to the traveling public there is nothing so exasperating as a train delay. It is fitting here also to say how appreciative the engineers of the New Haven road feel for the calm and generous suspension of judgment on the part of those engineers who have reserved opinion until it could be based on facts, which time only could so demonstrate as to permit presentation. There are many other little faults and difficulties here and there throughout the system, but the five described, though not fundamental in their effect, since they have been removed, were none the less the most serious.

### THE MINOR FAULTS

*Generator burn-outs.* Previously to the rearrangement of the feeders or the installation of the choke-coils in the power station, the short-circuits that were experienced on the line naturally had a deleterious effect on the generators. The prodigious rush of current naturally produced severe strains in the armature windings, strains whose mechanical intensity was made manifest by the movements of the coils. Therefore, during this period of violent short-circuits, frequently the generator coils were grounded and burned out. Since the rearrangement of feeders or the installation of choke-coils, the violent short-circuits have disappeared and with them the damaging effects on the generators. It has been found advisable, from time to time, to connect different generator terminals to the line. By this arrangement the three phases of the generators are in turn worked equally.

*Distribution.* Although the arrangement of the line in its present feed and trolley connections (Fig. 5) effects the highest economy in loss of power by transmission, it is questionable to

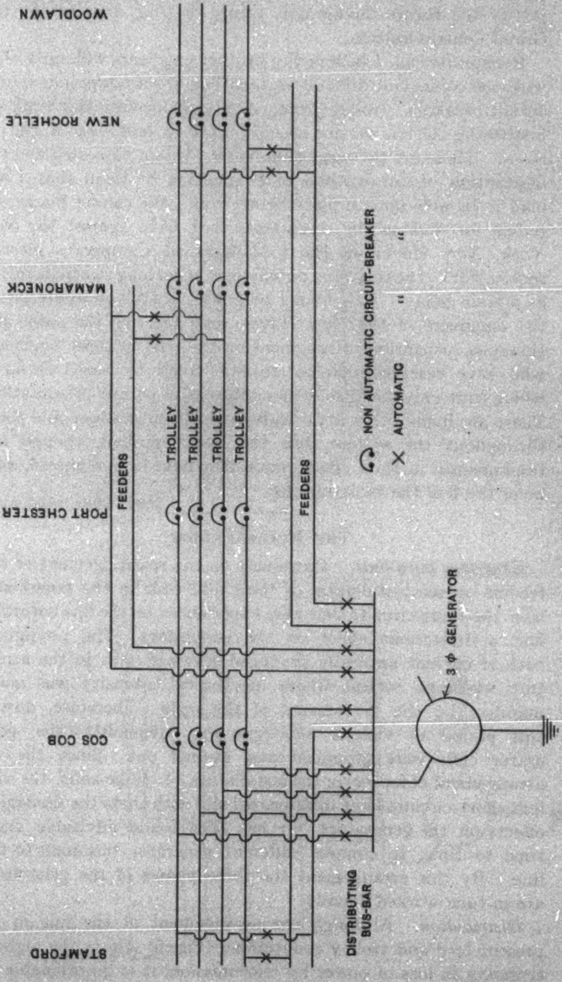
WOODLAWN
NEW ROCHELLE
MAMARONECK
PORT CHESTER
COS COB
STAMFORD
FEEDERS
TROLLEY
TROLLEY
TROLLEY
TROLLEY
FEEDERS
NON AUTOMATIC CIRCUIT-BREAKER
AUTOMATIC " "
3 Φ GENERATOR
DISTRIBUTING BUS-BAR

FIG. 6—Multiple track circuits

my mind whether this economy is worth some of the disadvantages which accrue from this arrangement. Until we had experienced the heavy current surges, due to short-circuits, it seemed reasonable that, should a short-circuit occur on the line, the two circuit-breakers which immediately fed that short-circuit would be the ones to respond. We were quite correct in this conclusion, but did not go far enough, as other circuit-breakers seemed to feel it their duty to relieve the situation and their location with respect to the correctly involved breakers was quite varied. Of course the ideal condition would be to have only the two breakers adjacent to the short-circuit open, as by this arrangement the voltage would remain on all trolley wires except the one in which the ground is involved. This operation can be effected, and at the time of this writing an effort is being made to obtain these results in practice.

A method of line transmission (Fig. 2) less efficient than that described in the previous paragraph (using the same amount of copper for each case) is one in which each track has its own individual voltage supplied to it and is kept separate from the other trolleys.

*Contact wire.* While the auxiliary wire, as previously described, was the panacea of our difficulties, and has given an excellent account of itself since having first been placed in operation, it is fair to believe that an even more sparkless operation can be obtained from an auxiliary wire which, instead of being attached by a rigid clip to the overhead copper conductor, is simply suspended from it by a loop, thus permitting the contact wire to rise slightly as the upper pressure of the pantagraph shoe travels along its surface. The contact wire should be anchored by turn-buckles to permit slacking and straining of the wire in winter and summer seasons, respectively.

*Hard spots in line.* Irregularities in the contact wire may be due to two causes. First, those that exist in the wire as it is manufactured; secondly, those formed on account of hard spots. The former can be taken out; if not, they are usually ironed out in the course of the operation of the shoe on the trolley. The three principal sources of hard spots are hangers, section breaks, and deflectors.

1. It has been shown in the foregoing how the hanger hard spots have been eliminated.

2. The original main-line section break consisted of a rectangular impregnated wood frame suspended under the anchor

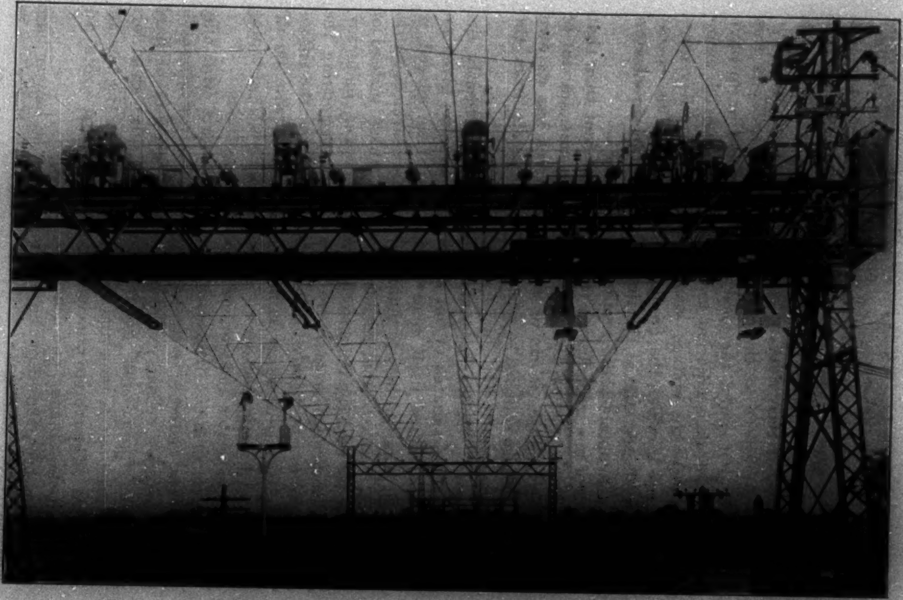

FIG. 7—End-on view of one new and three old section breaks

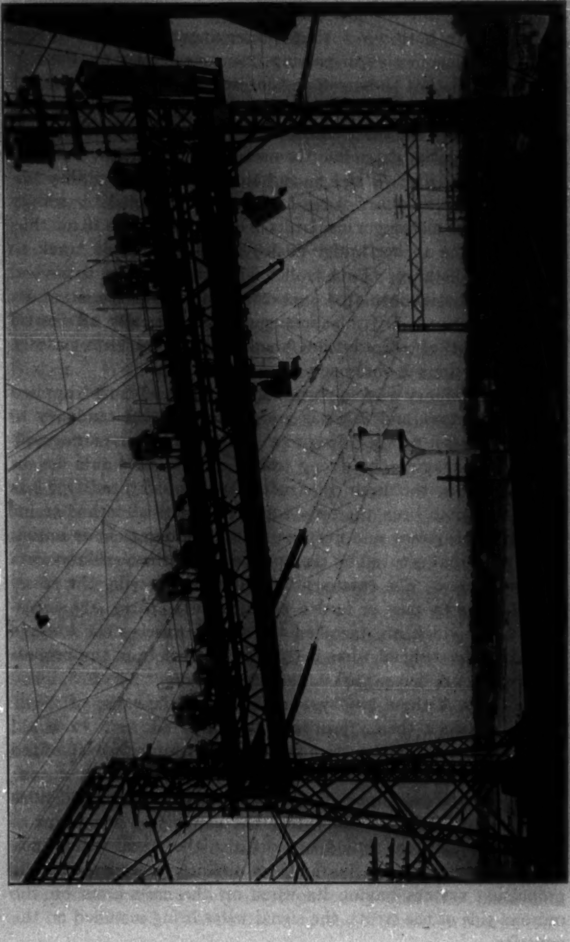

FIG. 8—Three-quarters view of one new and three old section breaks

bridges. The trolley wires were carried on opposite sides of this rectangle lapping, of course, a sufficient distance in the center to permit a short period of simultaneous contact of the shoe with both wires, thus preserving continuity of current to the locomotive in passing from one section to another. It was found that these rectangular section breaks were prone to get out of shape, introducing a very rough spot in the line, its effect being, on the passage of the shoe, to draw long arcs which frequently extended themselves to ground. Our new section break, Figs. 7 and 8, containing all the flexibility obtained by the auxiliary wire, has been constructed by simply staggering the messenger insulators of each trolley wire 16 in., thus permitting the anchor bridge trolley wires of the same track to pass at this distance. Each trolley wire is dead-ended to a wood impregnated stick insulator, supported by the messenger of its opposite section. By this arrangement practically all inertia is taken out of the section break and a sparkless passage between sections is obtained.

3. The auxiliary wire construction has been, of course, applied to the deflectors, and this has greatly reduced the tendency to spark at these points. In order to prevent the pantagraph shoe from engaging the wrong trolley wire at turn-outs on diverging tracks, the mesh construction of the overhead frog has up to this time been the only solution, but this method seems unduly cumbersome and even a greater improvement is anticipated than that secured by the application of the auxiliary wire.

*Signal wires*. The catenary bridge struts carrying the cross-arms for the by-pass or feeder wires, likewise carry the cross-arms upon which are installed the signal wires. The voltage placed on these signal wires is entirely distinct from the propulsion voltage, it being 2200 volts and 60 cycles. The proximity of the wires of these two systems has been the cause of short-circuits between them, resulting in double failures. It would seem that as the signal system should be so completely separated from the propulsion system, it should be installed on an entirely separate pole line. If, however, right-of-way conditions make it absolutely necessary that the supporting structures of the catenary system should support also the signal wires, then the two circuits should be made as distinctive as possible, the propulsion system having its wires on the cross-arms on the railroad side of the struts, the signal wires being installed on the opposite.

*Locomotive current collectors.* An efficient pantagraph shoe has proved itself a very difficult problem. The present cost is about .06 of a cent a locomotive-mile. We have made various experiments with aluminum, phono, copper, and steel rigid and spring-supported pantagraph shoes. While this feature does not present a serious aspect, it is none the less a most interesting study. Shoe life is also seriously affected by the amount of soot deposited by the locomotives upon the overhead wire. While we have obtained mileages varying between 600 and 1500 per shoe with various types used, other roads of lesser speed and not subject to the effect of locomotive stack discharges, have obtained as high as 25,000 shoe-miles.

## THE LOG OF OPERATION

*Electric passenger service.* So great was the demand for electric service that in July, 1907, long before we were ready, as the records of our operation have proved, the first commercial service was begun between New Rochelle and the Grand Central Station. With all speed possible the electrification was pushed eastward and local service was established from Port Chester in August, 1907. Local service from Stamford followed in October, and finally, on July 1, 1908, all through and local passenger trains were under electric schedule between Stamford and the Grand Central Station. It is, therefore, beginning from this date of July 1, 1908, that I have compiled data of our operation as taken from our records. We are not proud of it, but we believe that you now know of some of the obstacles that stood in the way of its immediate betterment at that time.

*Comparison between steam and electric service.* It had been the hope of the writer to be able, even at this early date, to make an absolute comparison between electric service and the steam service which it has replaced between Stamford and New York, including all passenger trains. On account of the speed restrictions that have been introduced on the electric service until all locomotives have been reconstructed with the new pony truck equipment, it is impossible to compare train-minute delays, for the reason that steam locomotives are permitted to make up time while to electric locomotives this privilege is denied. Later, when this restriction is removed, and especially after a period of time more extensive than that offered by the present comparatively short period of operation, these data can be presented. Particularly worthy of notation here in com-

### TABLE I.

TRAIN-MINUTES DELAY DURING JULY, 1908.

| Day | Power house | Line | Locomotive | Total | Cause of delay |
|---|---|---|---|---|---|
| 1 | .. | .. | 40 | 40 | Third-rail shoe. Air hose, third-rail. Train-line hose. One motor of locomotive grounded. Third-rail shoes. |
| 2 | .. | .. | 34 | 34 | Third-rail shoes. |
| 3 | .. | .. | 20 | 20 | Change-over switch direct-current fuses |
| 4 | .. | .. | 3 | 3 | Pantagraph. |
| 5 | .. | .. | .. | .. | No delays. |
| 6 | .. | 15 | .. | 15 | Circuit-breaker. |
| 7 | .. | .. | .. | .. | No delays. |
| 8 | .. | 57 | 3 | 60 | No power in direct-current rail. |
| 9 | .. | .. | 15 | 15 | Direct-current switch grounded. |
| 10 | .. | 13 | .. | 13 | Oil circuit-breaker. No power in direct-current rail. |
| 11 | .. | .. | .. | .. | No delays. |
| 12 | .. | .. | 16 | 16 | Control current from storage-batteries low. |
| 13 | .. | .. | .. | .. | No delays. |
| 14 | .. | .. | .. | .. | Over 300 train-minutes. |
| 15 | .. | 4 | 72 | 72 | Circuit-breaker. Preventive-coil ground. Pantagraph. Third-rail switch. Motorman failure. |
| 16 | .. | .. | .. | .. | Over 300 train-minutes. |
| 17 | .. | 12 | 29 | 41 | Insulator on foreign line broke. Change-over switch alternating-current coasting over gap at new bridge. |
| 18 | .. | .. | 7 | 7 | Direct current fuses. Stopping on gap at bridge. |
| 19 | .. | 34 | 47 | 81 | Line circuit-breaker. Pantagraph. |
| 20 | .. | .. | .. | .. | Over 300 train-minutes. |
| 21 | .. | 43 | 15 | 58 | Line circuit-breaker. Transformer grounded on locomotive. |
| 22 | .. | .. | 44 | 44 | Alternating-current controller. Pantagraph. |
| 23 | .. | .. | 41 | 41 | Pantagraph. |
| 24 | .. | .. | 3 | 3 | Alternating-current controller. |
| 25 | .. | .. | 124 | 124 | Pantagraph. Direct-current fuse. Alternating-current controller. Change-over switch. Motor grounded. |
| 26 | .. | .. | .. | .. | Over 300 train-minutes. |
| 27 | .. | .. | .. | .. | * * * * |
| 28 | .. | .. | 30 | 30 | Pantagraph. Grounded blower. |
| 29 | .. | 8 | 19 | 27 | Circuit-breaker (line). Transformer-lead ground on locomotive. |
| 30 | .. | 16 | .. | 16 | Circuit-breakers. |
| 31 | .. | .. | 21 | 21 | Third-rail shoes. Alternating-current switch. Pantagraph. |

## TABLE II.

### Train-Minutes Delay During August, 1908.

| Day | Power house | Line | Locomotive | Total | Cause of delay |
|---|---|---|---|---|---|
| 1 | .. | 5 | 3 | 8 | Circuit-breakers (line). Third-rail shoes. |
| 2 | .. | .. | 7 | 7 | Heavy train. |
| 3 | .. | .. | 12 | 12 | Third-rail shoes. Air hose. Pantagraph. |
| 4 | .. | .. | .. | .. | No delays. |
| 5 | .. | 12 | 10 | 22 | Pantagraph. Motor ground. Third-rail fuses. |
| 6 | .. | .. | .. | .. | Over 300 train-minutes. |
| 7 | .. | .. | .. | .. | No delays. |
| 8 | .. | .. | .. | .. | Over 300 train-minutes. |
| 9 | .. | 43 | .. | 43 | Circuit-breakers. |
| 10 | .. | 220 | 28 | 248 | Circuit-breakers (line). Locomotive circuit-breakers. Alternating-current switches. Resistance lead. |
| 11 | .. | 57 | 26 | 83 | Circuit-breakers (line). Change-over switch. Pantagraph. |
| 12 | .. | 5 | 2 | 7 | Line circuit-breakers open. Hot tire. |
| 13 | .. | .. | .. | .. | No delays. |
| 14 | .. | 19 | .. | 19 | Insulator. |
| 15 | .. | .. | 6 | 6 | Control (Alternating-current). Direct-current circuit-breaker. |
| 16 | .. | 64 | .. | 64 | Insulator. |
| 17 | .. | 3 | 43 | 46 | Circuit-breaker open (line). Ground. Direct-current shoes. Pantagraph. Preventive coil ground. Direct-current relay. |
| 18 | .. | 1 | 13 | 14 | Insulator. Line. Air hose. Third-rail shoe. |
| 19 | .. | .. | .. | .. | No delays. |
| 20 | .. | .. | .. | .. | " " |
| 21 | .. | .. | 8 | 8 | Hot box. Alternating-current control. |
| 22 | .. | 1 | 13 | 14 | Insulator. Line. 18 in. water direct-current zone. |
| 23 | .. | 5 | .. | 5 | Insulator. Line. |
| 24 | .. | 5 | 15 | 20 | Ground on signal wires. Pantagraph. |
| 25 | .. | 32 | 41 | 73 | Open circuit-breaker (line). Insulator (line). Hot box. Grounded motor. Third rail. Third-rail shoe. |
| 26 | .. | .. | 73 | 73 | Grounds developed by flood direct-current zone |
| 27 | .. | .. | 64 | 64 | " " " " " " " |
| 28 | 69 | .. | 1 | 70 | Turbine failure. Third-rail shoe. |
| 29 | 63 | .. | 22 | 85 | Turbine failure. Engine dispatcher. Grounded motor. |
| 30 | .. | .. | 6 | 6 | Heavy train. Low-voltage direct-current. |
| 31 | .. | .. | 14 | 14 | Grounded compressor. Low-voltage direct-current. |

### TABLE III.

TRAIN-MINUTES DELAY DURING SEPTEMBER, 1908.

| Day | Power house | Line | Locomotive | Total | Cause of delay |
|---|---|---|---|---|---|
| 1 | .. | .. | 4 | 4 | Compressor. Pantagraph. |
| 2 | .. | .. | 9 | 9 | Air hose. |
| 3 | .. | 15 | 18 | 33 | Line ground. Alternating-current switch. |
| 4 | .. | .. | 26 | 26 | Alternating-current control. Low-voltage direct current Alternating-current control. Third-rail shoes—Ground direct-current switch. |
| 5 | .. | 4 | .. | 4 | Open circuit-breaker. |
| 6 | .. | .. | 3 | 3 | Low-voltage direct-current. |
| 7 | .. | .. | 10 | 10 | Third-rail fuses. |
| 8 | .. | .. | .. | .. | Over 300 train-minutes. |
| 9 | .. | 3 | .. | 3 | Line ground. |
| 10 | .. | .. | .. | .. | No delays. |
| 11 | .. | .. | 7 | 7 | Direct-current switch ground. |
| 12 | .. | .. | 10 | 10 | Motor ground. |
| 13 | .. | 2 | 5 | 7 | Line ground. Low-voltage direct-current. Pantagraph. |
| 14 | .. | .. | 8 | 8 | Pantagraphs. Alternating-current relay. |
| 15 | .. | .. | 8 | 8 | Preventive coil. Third-rail gap. |
| 16 | .. | .. | 4 | 4 | Preventive coil. |
| 17 | .. | .. | 28 | 28 | Locomotive wheels off track (pony truck). |
| 18 | .. | .. | .. | .. | No delays. |
| 19 | .. | .. | 9 | 0 | Preventive coil. Signals. |
| 20 | .. | .. | 1 | 1 | Third rail shoes. |
| 21 | .. | .. | 2 | 2 | Third rail shoes. |
| 22 | .. | .. | 10 | 10 | Hot tire. |
| 23 | .. | .. | 32 | 32 | Ground on reversing switch. |
| 24 | .. | .. | 3 | 3 | Hot box. Direct-current shoes. |
| 25 | .. | 20 | .. | 20 | Circuit-breaker (line). |
| 26 | .. | .. | .. | .. | Over 300 train-minutes. |
| 27 | .. | 16 | .. | 16 | Grounded insulator. |
| 28 | .. | 4 | 8 | 12 | Signal wires. Pantagraph—Third-rail shoe. |
| 29 | .. | 3 | 10 | 13 | Open circuit-breakers. Locomotive jumper grounded. |
| 30 | .. | 4 | .. | 4 | Line ground. |

## TABLE IV.

### TRAIN-MINUTES DELAY DURING OCTOBER, 1908.

| Day | Power house | Line | Locomotive | Total | Cause of delay |
|---|---|---|---|---|---|
| 1 | .. | .. | 18 | 18 | Nipple broken on train line pipe. |
| 2 | .. | .. | .. | .. | No delays. |
| 3 | .. | .. | 3 | 3 | Motor ground. |
| 4 | .. | 14 | 1 | 15 | Splicing ear. Direct current shoes. |
| 5 | .. | .. | 7 | 7 | Pantagraph. Alternating-current switch. |
| 6 | .. | .. | 4 | 4 | Change-over |
| 7 | .. | .. | 9 | 9 | Alternating current switch. Air hose. |
| 8 | .. | .. | 10 | 10 | Direct-current fuses. Third-rail shoes. |
| 9 | .. | 22 | 4 | 26 | Circuit-breaker open. Direct-current switch. Direct-current shoes (third rail). |
| 10 | .. | 61 | .. | 61 | Open circuit-breakers. |
| 11 | .. | .. | .. | .. | No delays. |
| 12 | .. | .. | 9 | 9 | Pantagraph. Motor ground. Brakes sticking. |
| 13 | .. | .. | 4 | 4 | Direct-current relay. Pantagraph. Low direct-current voltage. |
| 14 | .. | 3 | .. | 3 | Open circuit-breaker. |
| 15 | .. | 15 | .. | 15 | Line ground. |
| 16 | .. | .. | .. | .. | Over 300 train-minutes. |
| 17 | .. | .. | 9 | 9 | Pantagraph. Control, direct-current. |
| 18 | .. | .. | .. | .. | No delays. |
| 19 | .. | .. | 10 | 10 | Direct-current circuit-breaker. Direct-current control. |
| 20 | .. | 4 | .. | 4 | Insulator. |
| 21 | .. | 3 | .. | 3 | Open circuit-breaker. |
| 22 | .. | .. | 5 | 5 | Grid resistance. |
| 23 | .. | .. | 10 | 10 | Air hose. |
| 24 | .. | .. | 3 | 3 | Third-rail shoes. |
| 25 | .. | .. | .. | .. | No delays. |
| 26 | .. | 70 | 19 | 89 | Grounded insulator. Hot box. |
| 27 | .. | 54 | 19 | 73 | Hot box. Insulator breakdown. Line ground. |
| 28 | .. | .. | 63 | 63 | Direct-current resistance ground. Hot box. Pneumatic control. |
| 29 | .. | 31 | 82 | 113 | Man failure. Grounded feeder. Direct-current circuit-breaker. Motor ground. Direct-current switch ground. Alternating-current switch. Third rail gap. |
| 30 | .. | .. | 42 | 42 | Direct-current switch ground. Man failure. |
| 31 | .. | .. | 12 | 12 | Direct-current relay. Motor flash-over. Pantagraph. |

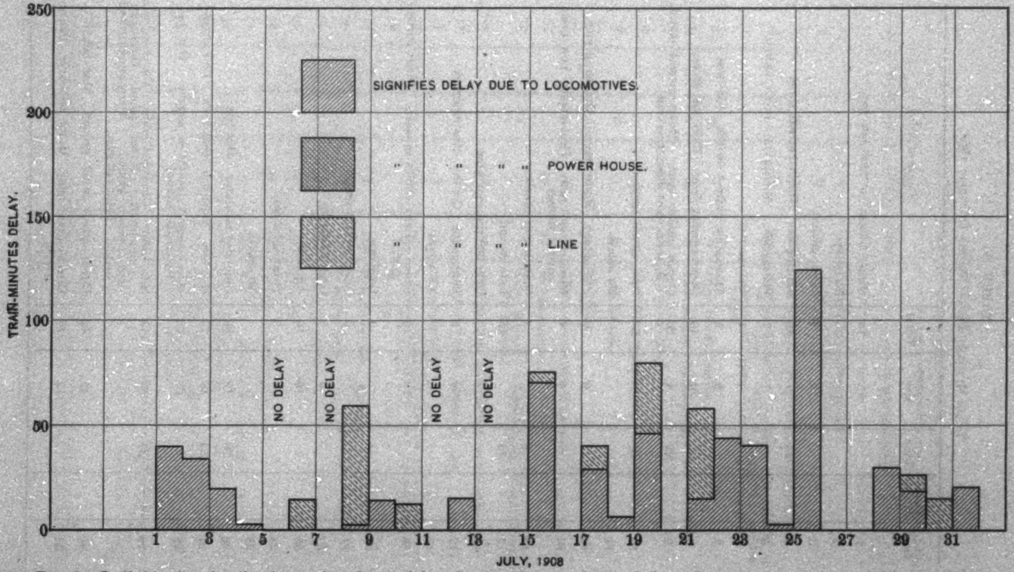

Fig. 9—Individual and collective train-minute delays in electric zone due to failures in power house, line, and locomotives

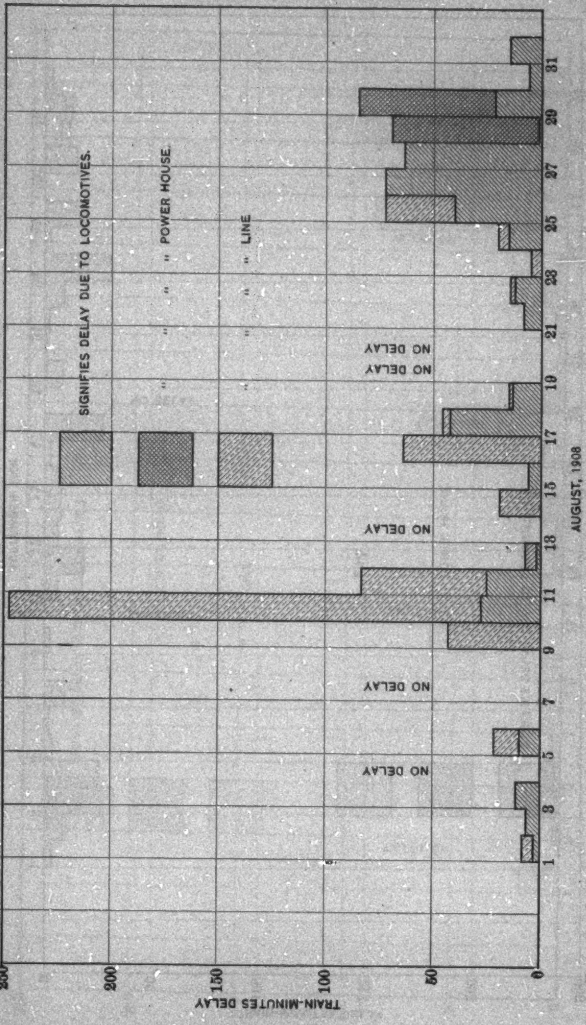

Fig. 10—Individual and collective train-minute delays in electric zone due to failures in power house, line, and locomotives

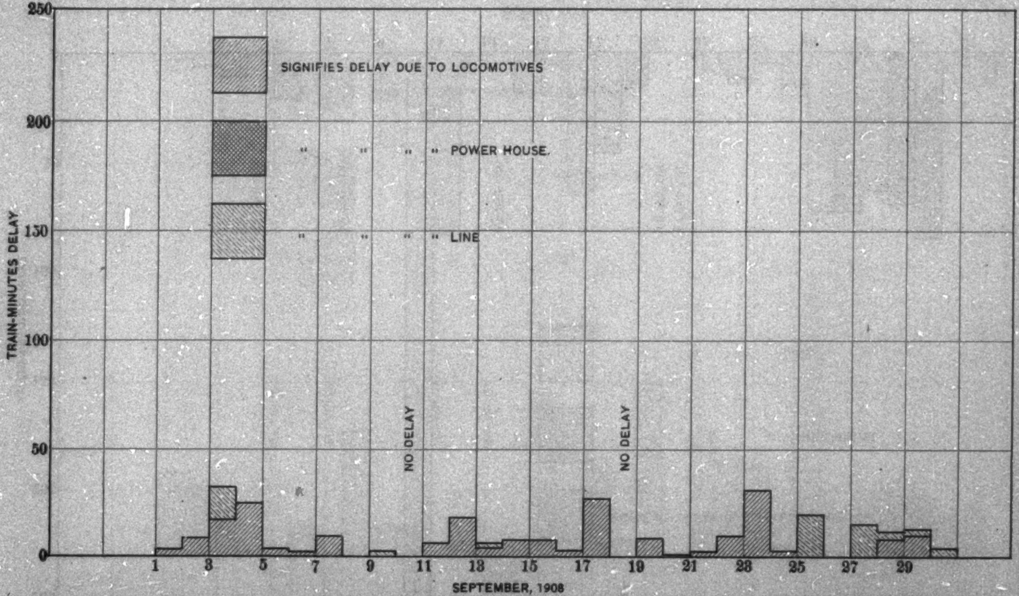

FIG. 11—Individual and collective train-minute delays in electric zone due to failures in power house, line, and locomotives

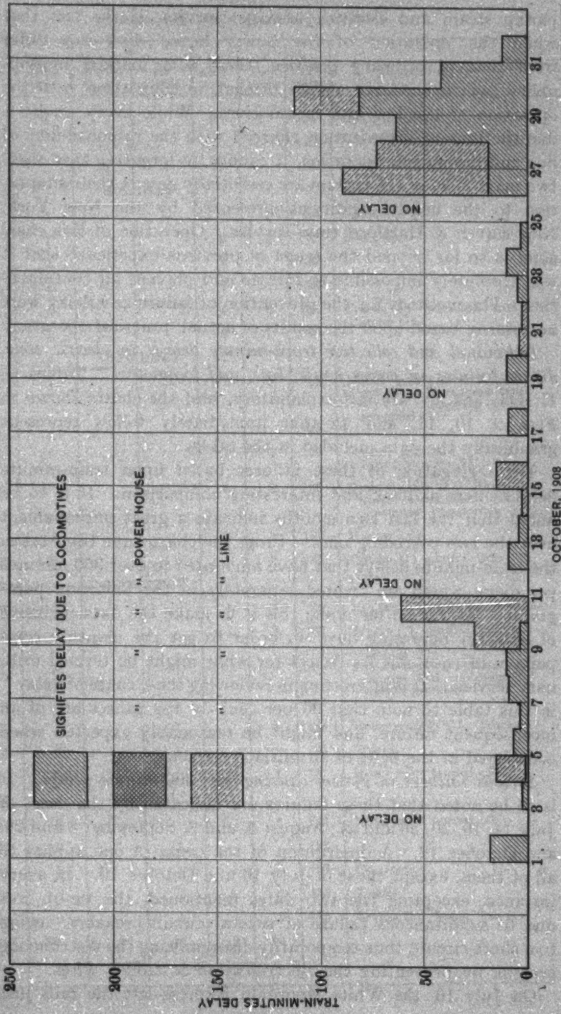

FIG. 12—Individual and collective train-minute delays in electric zone due to failures in power house, line, and locomotives

paring steam and electric passenger service, is the fact that while the operation of the power house does not differ from that of ordinary practice, there is a marked individuality (which initiative always brings), in connection with the operation of the line and locomotives. While every credit is due the present organization charged with the responsibility of line and locomotive operation, it cannot be forgotten that these two main links of the system are essentially new in their adaptation to the heavy conditions presented by the New York, New Haven & Hartford train service. Operation of this character is so far beyond the scope of previous experience that it was absolutely impossible to foresee and prevent all contingencies. The methods for the prevention of failure and delay were necessarily based upon the results of actual, practical operation.

*Individual and collective train-minute delays in electric zone, due to failures in power house, line, and locomotive.* Tables I, II, III, and IV are self-explanatory, and the charts shown in Figs. 9, 10, 11, and 12 that immediately follow represent graphically the data included in the tables.

The segregation of these failures based upon train-minute delays offers a quick and interesting comparison. It is to be noted that the last two months indicate a great improvement over the two preceding ones. From the chart have been taken the train-minute delays that have amounted to over 300 minutes per diem, which are treated separately in the following paragraph. My reason for doing this is to make the data inclusive of ordinary operating days, in order to get the monthly comparison of train-minute delays for what might be termed ordinary service. It is interesting in reviewing the " cause of delay " in this table to note that 90 per cent. of the causes are of an inconsequent nature, and might be reasonably expected when considered in the light of an initiative service.

*Serious failures in system causing over* 300*-minute delays.* It is to be noted that these failures are indicated by the dates of July 14, 16, 20, 26 and 27; August 6, and 8; September 8 and 26, and October 19. A description of the cause of one applies to all of them, except those of July 16 and October 19. In every instance, excepting the two dates mentioned, the tie-up was due to simultaneous failure of several circuit-breakers, owing to a short-circuit, thus temporarily disorganizing the distributing system, by preventing the electrification of trolley wires.

On July 16, the White Mountain Express left the rails just

### TABLE V.

Locomotive Daily Reports, July, 1908.

| Date | Reconstruction | Experimental & test | Trucks installed | Inspection | Repairs | No. of trains | Cause of repairs |
|---|---|---|---|---|---|---|---|
| 1 | 1 | .. | .. | 2 | 1 | 136 | Grounded motor. |
| 2 | .. | .. | .. | .. | .. | 142 | |
| 3 | .. | .. | .. | .. | ... | 148 | |
| 4 | ... | HOL | IDAY | .. | .. | .. | |
| 5 | 1 | .. | .. | .. | 1 | 81 | Loose tire. |
| 6 | 1 | .. | .. | 2 | 1 | 140 | Loose tire. |
| 7 | 1 | .. | .. | 2 | .. | 135 | |
| 8 | 1 | .. | .. | 2 | .. | 135 | |
| 9 | 1 | .. | ... | 1 | 2 | 135 | Trucks (1) grounded switch group (1). |
| 10 | 1 | .. | .. | 2 | .. | 135 | |
| 11 | .. | SATU | RDAY | ... | .. | ... | |
| 12 | 1 | .. | .. | .. | 3 | 69 | Direct-current shunt burned out (1). Tramming truck (1). Change-over switch grounded (1). |
| 13 | 1 | .. | .. | 1 | .. | 135 | |
| 14 | 1 | .. | .. | .. | 2 | 135 | Broken axle (1). Changing spring-hangers (1) |
| 15 | 1 | .. | .. | 1 | 3 | 135 | Broken axles (1). Short-circuited commutator (1). Grounded transformer (1). |
| 16 | 1 | .. | .. | 3 | 1 | 132 | Broken axle. |
| 17 | 2 | .. | .. | .. | 2 | 135 | Trucks (1) slipped tires. |
| 18 | .. | SATU | RDAY | .. | .. | .. | |
| 19 | 2 | 1 | .. | 1 | 2 | 68 | Hot box (1). Changing motors (1). |
| 20 | 2 | .. | .. | .. | 3 | 135 | Trucks (1). Burned-out transformer (1). Change-over trouble (1). |
| 21 | 3 | .. | 1 | .. | 4 | 135 | Transformer grounded (3). Blower and compressor motors grounded (1). |
| 22 | 3 | .. | 1 | .. | .. | 135 | |
| 23 | 2 | .. | 1 | .. | 2 | 135 | Motor trouble (1). Trucks. |
| 24 | 2 | .. | 1 | .. | 1 | 135 | Trucks. |
| 25 | 2 | .. | 1 | .. | 1 | 137 | Motor leads burned off. |
| 26 | .. | SUN | DAY | .. | .. | .. | |
| 27 | 2 | .. | .. | .. | 1 | 133 | Motor leads burned off. |
| 28 | 2 | 1 | 1 | .. | .. | 133 | |
| 29 | 2 | .. | 1 | 1 | 1 | 133 | Side motion. |
| 30 | 1 | .. | 1 | 1 | 1 | 133 | Trucks. |
| 31 | 1 | .. | 1 | .. | 2 | 135 | Trucks (1). Loose tires (1). |
| Total | 38 | 2 | 10 | 19 | 34 | | |
| Avg. | 1.41 | 0.074 | 0.37 | 0.71 | 1.26 | | |

TABLE VI.
LOCOMOTIVE DAILY REPORTS, AUGUST, 1908.

| Date | Reconstruction | Experimental & test | Trucks installed | Inspection | Repairs | No. of trains | Cause of repairs |
|---|---|---|---|---|---|---|---|
| 1 | 1 | .. | 1 | .. | 1 | 141 | Trucks. |
| 2 | .. | SUN | DAY | .. | .. | .. | |
| 3 | 2 | .. | 1 | .. | 2 | 135 | Truck springs (1). Blower motors (1). |
| 4 | 2 | .. | 1 | 1 | .. | 133 | |
| 5 | 1 | .. | 1 | 1 | 1 | 134 | Changing motors. |
| 6 | 1 | .. | 1 | 2 | 1 | 131 | Changing motors. |
| 7 | .. | .. | 1 | .. | 2 | 133 | Compressor grounded (1). Trucks and reconstruction. |
| 8 | 1 | 1 | .. | .. | 2 | 136 | No. 1 Main Reservoir leaking. Trucks and reconstruction (1). |
| 9 | .. | SUN | DAY | .. | .. | .. | |
| 10 | 1 | .. | .. | .. | 1 | 135 | Trucks and reconstruction. |
| 11 | 1 | .. | .. | 1 | 1 | 133 | Trucks and reconstruction. |
| 12 | 1 | .. | .. | .. | 3 | 133 | Grounded direct-current relay (1). Loose tires (1). Trucks and reconstruction (1). |
| 13 | 1 | .. | .. | .. | 1 | 132 | Trucks and reconstruction. |
| 14 | 1 | .. | .. | .. | 1 | 134 | Waiting for wheels from Readville. |
| 15 | 1 | .. | .. | .. | 1 | 138 | Waiting for wheels from Readville. |
| 16 | .. | SUN | DAY | .. | .. | .. | |
| 17 | 1 | 1 | .. | 1 | 2 | 133 | Direct-current shoe cables grounded. Waiting for wheels from Readville (1). |
| 18 | 1 | .. | .. | .. | 3 | 133 | Circuit-breaker trouble (1). Direct-current shoe cables grounded. Waiting for wheels from Readville (1). |
| 19 | 1 | .. | .. | .. | 1 | 133 | Waiting-wheels. Readville. |
| 20 | 1 | .. | .. | 1 | 1 | 133 | Changing compressor. |
| 21 | 2 | .. | .. | 1 | .. | 133 | |
| 22 | 2 | .. | .. | 2 | .. | 137 | |
| 23 | .. | SUN | DAY | .. | .. | .. | |
| 24 | 2 | .. | .. | .. | 1 | 135 | Grounded motor. |
| 25 | 2 | .. | .. | .. | 2 | 133 | Grounded motor (1). Grounded armature (1). |
| 26 | 2 | .. | .. | .. | 9 | 133 | Grounds, due flood, N. Y. Central zone. |
| 27 | 2 | .. | .. | .. | 5 | 133 | M-1 switch-group grounded. Grounds, due flood—N. Y. Central zone (4). |
| 28 | 2 | .. | .. | .. | 2 | 133 | Grounds, due flood—N. Y. Central zone. |
| 29 | 2 | .. | .. | .. | 2 | 141 | Grounded motors (2). |
| 30 | .. | SUN | DAY | .. | .. | .. | |
| 31 | 2 | 1 | .. | .. | .. | 143 | |
| Total | 36 | 3 | 6 | 10 | 45 | 3502 | (Total daily trains). |
| Avg. | 1.39 | 0.11 | 0.23 | 0.39 | 1.73 | 135 | (Average). |

## TABLE VII.

### Locomotive Daily Reports, September, 1903.

| Date | Reconstruction | Experimental & test | Trucks installed | Inspection | Repairs | No. of trains | Cause of repairs |
|---|---|---|---|---|---|---|---|
| 1 | 2 | .. | 1 | .. | .. | 137 | |
| 2 | 2 | .. | 1 | 1 | 1 | 135 | Grounded motor. |
| 3 | 2 | .. | 1 | 1 | .. | 134 | |
| 4 | 2 | .. | 1 | .. | 1 | 139 | Grounded motor. |
| 5 | 1 | .. | 1 | .. | 1 | 148 | Grounded compressor motor. |
| 6 | .. | SUN | DAY | .. | .. | .. | |
| 7 | .. | LABO | R DAY | .. | .. | .. | |
| 8 | 2 | .. | 1 | .. | .. | 143 | |
| 9 | 2 | .. | 1 | .. | .. | 138 | |
| 10 | 2 | .. | 2 | .. | .. | 138 | |
| 11 | 2 | .. | 1 | 1 | 1 | 137 | M-1 Switch grounded. |
| 12 | 2 | .. | 1 | .. | 1 | 140 | M-1 Switch grounded. |
| 13 | .. | SUN | DAY | .. | .. | .. | |
| 14 | 2 | .. | 2 | .. | .. | 129 | |
| 15 | 2 | .. | 2 | .. | .. | 126 | |
| 16 | 2 | .. | 1 | 1 | .. | 126 | |
| 17 | 3 | .. | 2 | 1 | .. | 126 | |
| 18 | 3 | .. | 2 | 1 | .. | 126 | Trucks. |
| 19 | 3 | .. | 2 | .. | .. | 130 | |
| 20 | .. | SUN | DAY | .. | .. | .. | |
| 21 | 3 | .. | 2 | .. | 1 | 130 | Change-over switch grounded. |
| 22 | 2 | 2 | 2 | .. | 1 | 127 | Change-over switch grounded. |
| 23 | 2 | .. | 2 | .. | 1 | 126 | Change-over switch grounded. |
| 24 | 3 | .. | 3 | .. | .. | 126 | |
| 25 | 2 | .. | 2 | .. | 1 | 126 | Sharp flanges. |
| 26 | 3 | .. | 2 | .. | .. | 128 | |
| 27 | .. | SUN | DAY | .. | .. | .. | |
| 28 | 3 | .. | 2 | .. | .. | 128 | |
| 29 | 3 | .. | 2 | .. | .. | 126 | |
| 30 | 3 | .. | 2 | .. | .. | 126 | |
| Total | 58 | 2 | 41 | 5 | 10 | 3295 | (Total daily trains.) |
| Avg. | 2.32 | 0.08 | 1.64 | 0.20 | 0.40 | 132 | (Average.) |

### TABLE VIII.

LOCOMOTIVE DAILY REPORTS, OCTOBER, 1908.

| Date | Reconstruction | Experimental & test | Trucks installed | Inspection | Repairs | No. of trains | Cause of repairs |
|---|---|---|---|---|---|---|---|
| 1 | 3 | 1 | 2 | .. | .. | 126 | |
| 2 | 3 | .. | 2 | .. | .. | 126 | |
| 3 | 3 | .. | 2 | .. | .. | 129 | |
| 4 | .. | SUN | DAY | .. | .. | .. | |
| 5 | 3 | .. | 2 | .. | .. | 126 | |
| 6 | 3 | 1 | 2 | .. | .. | 124 | |
| 7 | 3 | .. | 2 | .. | .. | 124 | |
| 8 | 3 | .. | 1 | .. | 1 | 125 | Sharp flanges. |
| 9 | 3 | .. | 2 | .. | .. | 125 | |
| 10 | 3 | 1 | 2 | .. | .. | 129 | |
| 11 | .. | SUN | DAY | .. | .. | .. | |
| 12 | 3 | .. | 2 | .. | .. | 125 | |
| 13 | 3 | 1 | 2 | .. | .. | 126 | |
| 14 | 3 | .. | 2 | .. | .. | 124 | |
| 15 | 3 | .. | 2 | .. | .. | 124 | |
| 16 | 3 | 1 | 2 | .. | .. | 124 | |
| 17 | 3 | .. | 2 | .. | .. | 126 | |
| 18 | .. | SUN | DAY | .. | .. | .. | |
| 19 | 3 | .. | 3 | .. | .. | 125 | |
| 20 | 3 | 1 | 2 | .. | 1 | 124 | Turning flanges. |
| 21 | 3 | .. | 3 | .. | .. | 126 | |
| 22 | 3 | .. | 3 | .. | .. | 124 | |
| 23 | 3 | .. | 2 | .. | 1 | 125 | Grounded motor. |
| 24 | 3 | 1 | 2 | .. | .. | 126 | |
| 25 | .. | SUN | DAY | .. | .. | .. | |
| 26 | 3 | .. | 3 | .. | .. | 125 | |
| 27 | 4 | .. | 2 | .. | .. | 124 | |
| 28 | 4 | .. | 3 | .. | .. | 124 | |
| 29 | 4 | .. | 2 | .. | .. | 124 | |
| 30 | 3 | .. | 3 | .. | .. | 124 | |
| 31 | 3 | .. | 3 | .. | .. | 126 | |
| Total | 84 | 7 | 60 | | 3 | 3380 | (Total week-day trains.) |
| Avg. | 3.10 | 0.26 | 2.22 | | 0.11 | 1250 | (Average.) |

## TABLE IX.

### ELECTRIC LOCOMOTIVE-MILEAGE DATA FOR SEPTEMBER 5, 1908.

| No. of Engine | No. of runs made | Main Line Mileage |
|---|---|---|
| 01 | In shop | |
| 02 | 7 | 238 |
| 03 | 7 | 230 |
| 04 | 7 | 206 |
| 05 | 4 | 136 |
| 06 | In shop | |
| 07 | 4 | 111 |
| 08 | 3 | 102 |
| 09 | 8 | 256 |
| 010 | 8 | 264 |
| 011 | 5 | 170 |
| 012 | 7 | 196 |
| 013 | 8 | 245 |
| 014 | 6 | 188 |
| 015 | 8 | 247 |
| 016 | 5 | 162 |
| 017 | In shop | |
| 018 | 5 | 136 |
| 019 | 10 | 340 |
| 020 | 6 | 188 |
| 021 | 8 | 264 |
| 022 | 7 | 204 |
| 023 | 9 | 306 |
| 024 | 4 | 136 |
| 025 | 7 | 222 |
| 026 | 8 | 264 |
| 027 | 9 | 306 |
| 028 | 8 | 272 |
| 029 | 6 | 196 |
| 030 | 6 | 188 |
| 031 | 8 | 272 |
| 032 | 6 | 187 |
| 033 | 3 | 102 |
| 034 | 4 | 135 |
| 035 | 8 | 272 |
| 036 | 4 | 136 |
| 037 | 7 | 238 |
| 038 | 6 | 196 |
| 039 | 7 | 230 |
| 040 | 7 | 238 |
| 041 | 8 | 272 |
| Total | 248 | 8051 |
| Average | 6.5 | 212 |

Main line mileage does not include switching.
Maximum mileage made, 340.
Average mileage, 212.

east of Greenwich station, tying up both east-bound tracks, and causing excessive train-minute delays. Except for the electric rail-bonds which suffered destruction, no other electrical apparatus was disturbed. One of the electric locomotives attached to this train was immediately returned to service, the other following it the next day after light repairs were made to its pilot and third-rail shoe mechanism.

On October 19, although the impedance coils in the generator station were in action, a ground occurring on the bus-bars of the anchor bridge directly outside of the power station, in combination with a defective circuit-breaker, produced a short-circuit which destroyed the operating mechanism of the breaker in question. This unfortunately occurred at a time when temporary connections had been made between the power house and line; on this account a serious delay was experienced in restoring the voltage to the line.

It is interesting to note that since the complete inauguration of electric service, the serious failures in the system have been reduced from five to one.

*Engine repairs.* Under " faults " is described the necessity in detail of our engine reconstruction. Since 100 per cent. service has been established, it has occurred to me that the shop reports concerning the daily number of engines which are out of service on account of repairs or for other reasons, would be interesting. On account of the reconstruction being done on the locomotives, it has been found necessary to give up on an average three electric locomotives at Stamford and three at New Haven, the new bogie trucks being installed on the engines at New Haven. Thus out of 41 locomotives we have had only 35 to handle the complete passenger service. This has resulted in requiring that the New Haven locomotives handle the service with virtually no spare engines. An examination of Tables V, VI, VII and VIII, under columns " Inspection " and " Repairs ", indicating how few have been the engines in the shop for the past three months, is an attest of this requirement.

*The capacity of the electric locomotive.* The capacity of the electric locomotives was based upon their ability to handle a trailing load of 200 tons in local service with stops averaging those that exist between stations from New York to New Haven. As a matter of fact, the station stops between Stamford and New York average very much greater than between New Haven and New York, and as very quick turns are made

## TABLE X.

### Trailing Loads in Excess of Locomotive Guarantees.

| Date | Service | Train No. | Locomotive No. | Trailing train weight | Percentage over weight |
|---|---|---|---|---|---|
| 10/18 | S. Ex. | 59 | 07-024 | 538 | 7.6 |
| | S. Ex. | 18 | 04-09 | 623 | 24.8 |
| | S. Ex. | 1 | 038-041 | 604 | 20.8 |
| | S. Ex. | 2 | 04-027 | 682 | 36.4 |
| 10/19 | S. Ex. | 21 | 038 | 284 | 13.6 |
| | S. Ex. | 15 | 028 | 327 | 30.8 |
| | S. Ex. | 45 | 040-041 | 561 | 12.8 |
| | S. Loc. | 215 | 08 | 236 | 18.0 |
| | S. Ex. | 63 | 030 | 302 | 20.8 |
| | P. C. Loc. | 181 | 041 | 348 | 39.2 |
| | S. Ex. | 269 | 034 | 277 | 10.8 |
| | S. Ex. | 1 | 06-036 | 674 | 34.8 |
| | S. Ex. | 29 | 01 | 280 | 12.0 |
| | S. Ex. | 2 | 04-09 | 609 | 22.0 |
| 10/20 | S. Ex. | 2 | 03-08 | 762 | 52.0 |
| | S. Ex. | 1 | 030-033 | 684 | 36.8 |
| | P. C. Loc. | 181 | 040 | 314 | 25.6 |
| | N. R. Loc. | 151 | 023 | 344 | 14.7 |
| | S. Loc. | 252 | 020 | 235 | 17.5 |
| | S. Ex. | 11 | 07-024 | 560 | 12.0 |
| | S. Ex. | 15 | 013 | 400 | 60.0 |
| | S. L. Ex. | 260 | 034 | 273 | 9.2 |
| 10/21 | S. Ex. | 21 | 07 | 331 | 32.3 |
| | S. Loc. | 287 | 04 | 223 | 11.5 |
| | S. L. Ex. | 260 | 03 | 271 | 8.4 |
| | S. L. Ex. | 246 | 038 | 283 | 13.4 |
| | S. Ex. | 15 | 040 | 332 | 32.7 |
| | S. Loc. | 216 | 026 | 256 | 28.0 |
| | S. Loc. | 252 | 033 | 275 | 37.5 |
| | S. Loc. | 206 | 038 | 257 | 28.5 |
| | N. R. Loc. | 151 | 010 | 338 | 12.7 |
| | S. Loc. | 207 | 025 | 262 | 31.0 |
| | P. C. Loc. | 181 | 09 | 297 | 18.8 |
| | S. Ex. | 1 | 032-037 | 698 | 39.5 |
| | S. Ex. | 29 | 010 | 280 | 12.0 |
| | S. Ex. | 2 | 07-032 | 817 | 63.6 |
| 10/22 | S. Ex. | 21 | 010 | 328 | 31.2 |
| | S. Ex. | 55 | 040 | 317 | 26.7 |
| | S. Loc. | 287 | 026 | 226 | 13.0 |
| | S. L. Ex. | 260 | 02 | 285 | 14.0 |
| | S. L. Ex. | 246 | 016 | 274 | 9.6 |
| | S. Ex. | 245 | 037 | 279 | 11.6 |
| | S. Ex. | 15 | 034 | 391 | 16.4 |
| | S. Loc. | 252 | 034 | 281 | 40.5 |
| | S. Loc. | 222 | 011 | 222 | 11.0 |
| | S. Loc. | 206 | 037 | 251 | 25.5 |
| | N. R. Loc. | 151 | 030 | 343 | 14.3 |
| | P. C. Loc. | 181 | 033 | 302 | 20.8 |
| | S. Ex. | 1 | 06-038 | 668 | 33.6 |
| | S. Ex. | 29 | 028 | 271 | 8.4 |
| | S. Ex. | 2 | 04-038 | 700 | 40.0 |

| Date | Service | Train No. | Locomotive No. | Trailing train weight | Percentage over weight |
|---|---|---|---|---|---|
| 10/23 | S. Ex. | 21 | 013 | 339 | 35.6 |
| | S. Ex. | 55 | 012 | 320 | 28.0 |
| | S. L. Ex. | 246 | 02 | 263 | 5.2 |
| | S. Ex. | 15 | 010 | 377 | 50.8 |
| | S. Ex. | 11 | 05–08 | 542 | 8.4 |
| | S. Ex. | 56 | 024 | 313 | 25.2 |
| | S. Loc. | 252 | 027 | 269 | 34.5 |
| | S. Loc. | 215 | 09 | 241 | 20.5 |
| | S. Loc. | 206 | 02 | 233 | 16.5 |
| | S. Loc. | 207 | 03 | 245 | 22.5 |
| | P. C. Loc. | 181 | 028 | 318 | 27.2 |
| | S. Ex. | 1 | 017–041 | 747 | 9.6 |
| | S. Ex. | 2 | 03–011 | 853 | 70.4 |
| 10/24 | P. C. Loc. | 190 | 012 | 281 | 12.4 |
| | S. L. Ex. | 292 | 010 | 258 | 3.2 |
| | S. Ex. | 15 | 019 | 333 | 33.2 |
| | S. Ex. | 24 | 06 | 396 | 58.4 |
| | S. L. Ex. | 288 | 02 | 258 | 3.2 |
| | P. C. Loc. | 176 | 022 | 298 | 19.2 |
| | P. C. Loc. | 172 | 037 | 290 | 16.0 |
| | S. Loc. | 212 | 041 | 245 | 32.5 |
| | N. R. Loc. | 151 | 029 | 323 | 7.7 |
| | S. Loc. | 207 | 06 | 246 | 23.0 |
| | P. C. Loc. | 181 | 033 | 299 | 19.6 |
| | S. Ex. | 1 | 019–036 | 624 | 24.8 |
| | S. Ex. | 29 | 08 | 271 | 8.4 |
| | S. Ex. | 2 | 026–030 | 819 | 63.9 |

at both termini, the service may be said to be more severe under these conditions than under the guaranteed conditions of purchase. It is interesting to note in Table X the trailing loads, taken at random, hauled by the New Haven electric locomotives for the week ending October 24, 1908.

*Comparative steam and electric engine mileage.* September 5, last, Labor Day, offered an interesting day to note what mileages could be made by the electric locomotives. Table IX gives an individual record for each of the 38 electric locomotives in service that day.

In obtaining an average for all electric locomotives of 212 miles, it is to be remembered that this was made for all classes of service, express, express-local, and local, and further that the mileages were made over three short terminal runs; namely, Stamford, Portchester, and New Rochelle to New York, the distances being approximately 34, 26, and 17 miles, respectively. As indicated in the table, several engines made eight runs, two of them nine, and one ten. It is difficult to get an exact comparison for steam locomotive mileages. All of the electric engines are confined to one division, while the steam locomotives do interdivision service. However, using the records of the 1906 steam service for Labor Day and considering steam locomotives doing mileage in and out of the present electric zone, out of 117 locomotives the following record is to be noted:

10 made over 300 miles.
20 " between 200 and 300 miles
21 " " 150 and 200 "
34 " " 100 and 150 "
32 " under 100 miles.
117

Thus with division limits double that of the present electric division, and with the additional advantage of interdivision runs, the electric mileage for this concrete case averaged 34 per cent. better than the steam mileage.

### THE ELECTRIFICATION IN ITS RELATION TO MATTERS OTHER THAN TRACTION

*Telegraph and telephone.* Single-phase electrification affects telegraph and telephone systems whose wires lie parallel with and in close proximity to the railroad. The corrective for this disturbance has proved to be simple and not costly. Briefly described, it consists of compensating transformers whose secondaries are a part of the telegraph and telephone wires and whose primaries receive their voltage from pilot wires strung on the same cross-arms as those bearing the telegraph and telephone wires, and thus having impressed upon them the same voltage, by electromagnetic induction, as the telegraph and telephone wires. The transformer secondary voltage is approximately equal and opposite to the induced voltage on the telegraph and telephone wires and thus constantly compensates for it throughout all ranges of induction due to the single-phase wires.

An interesting commentary on the efficacy of the compensating transformer is that its use obviated the necessity of any change in the physical location of the telegraph and telephone lines within the zone of induction, and has thus been the means of removing what at first was rightly considered a very offensive attribute of the single-phase system.

*Public safety.* As no fatality to the traveling public has happened by reason of the high-voltage wires since the system has been in operation, this would indicate the safety involved in its construction. The catenary form of construction as applied to the suspension of the trolley wire virtually eliminates all danger of these wires falling. On the other hand, the feeder or by-pass wires are not suspended by messengers, and although the 300-ft. spans used in this construction are not uncommon, it has been considered a wiser policy to reinforce all such spans which are above passenger platform stations. It may be of interest to state also that the scheme of reinforcement is not to cradle or place supplementary wires in connection with this span, but simply to use a steel wire with a large factor of safety reinforced by copper for conductivity conductor and supported from the struts by insulators. The resistance to ground of this construction will be far in excess of the ordinary insulator used in the open construction, with the steel wire connected to it in such a manner as to make impossible the burning of this wire in two, in the case of the insulator breaking down.

*Foreign wires.* All electrifications are subject to foreign wire crossings. As in the case of suspension of high-voltage wires over passenger platforms, instead of using supplementary catenaries or cradles, the safer (and incidentally the cheaper) method of crossing is to use at the crossing heavier (and possibly guyed) poles, better insulation, and larger wires than are commercially necessary in the other parts of the foreign transmission line. High factors of safety with economy are obtained following this policy.

## COMMENTARY

*Lightning protection.* An ideal arrangement of catenary construction in relation to lightning protection would be to have the overhead messenger system grounded, and from it suspended by insulators a secondary catenary system, to which in turn would be attached the contact wires. Even in the New Haven case, where the overhead messenger system is not grounded, lightning has given but slight trouble. This is probably due to the very great number of grounded steel trusses and struts projecting above the electrified wires. Lightning was the indirect cause of one of our delays, but played only a small part in the real cause, which can be attributed to the surge of current occurring at the time lightning caused a ground. At that

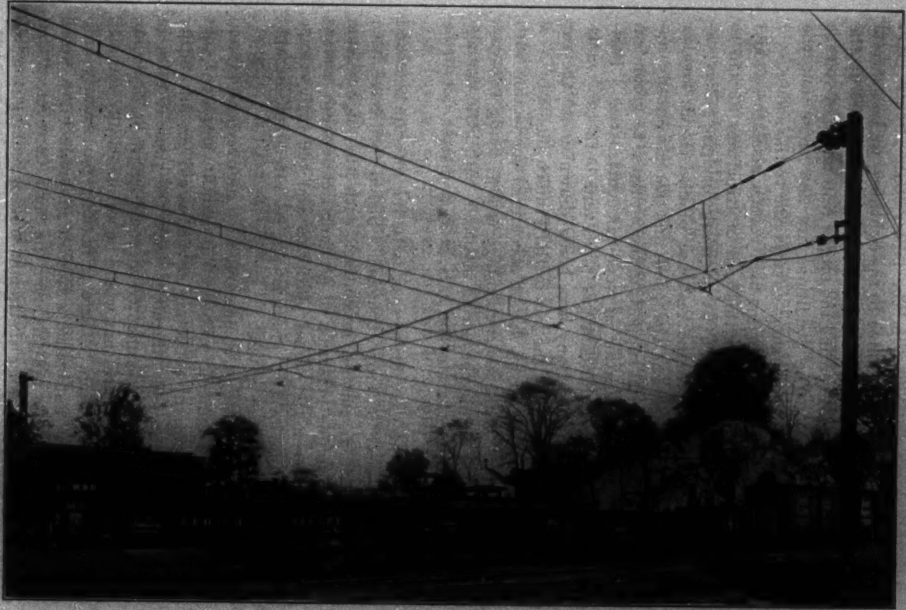

Fig. 13—Cross-catenary construction East Portchester yard.

time the feeders had not been rearranged, nor had the impedance coils been installed in the power-house circuits. On the occasion of this ground, due to the lightning, we lost several of the anchor bridge circuit-breakers; this naturally tied up the distributing system, preventing the proper restoration of voltage to the trolley wires. The conditions are now such that the circuit-breakers will relieve short-circuits due to this cause.

*Grounds*. Structures supporting high-voltage insulators should be grounded. Particularly is this true of structures foreign to the railroad company, such as highway bridges. This arrangement insures a prompt response of the circuit-breaker apparatus, and carries out the good practice universally applicable, that the material supporting the insulator be grounded. This principle has application in wood-car construction. Positive grounds between Pintsch gas pipes and both car trucks should be made to avoid any arcs being drawn under the car body. On two occasions the gas in the Pintsch mains of New Haven cars has been set on fire on account of connection with electrified wires. While the percentage is low, being two cars in about 400,000 during the period involved, with little damage in either case and that to the cars, it is a matter not to be ignored.

Many of our catenary bridges, of both the intermediate and anchor type, serve to support signals. Signal men have been entirely free from coming in contact with the high-tension wires, by the simple provision of grounded close-mesh screens interposed between the signal platforms and the high-voltage wires. The value of two grounds can be rated considerably higher than twice that of one.

*Tell-tales*. Tell-tales in connection with an overhead system offer a peculiarly difficult problem. It is quite apparent that the pantagraph current collecting device would get into either electrical or mechanical difficulties with the present form of tell-tales. We have experimented at some length in trying to produce an electrical horn that would be automatically sounded by an approaching train. There is nothing particularly difficult in getting the automatic action or in producing a noise. The superiority of the tell-tale over the horn, however, is that no matter how much noise the freight train is making, the tell-tale always notifies, while in the case of the horn, should the freight train be making more noise than it, the notification is lost. A horn if used for this service should be a large one.

As a matter of fact, the necessity of tell-tales is a bit of a relic of the barbaric past. In the days of hand brakes, the brakeman had to walk the roofs of cars, and low bridge warnings were necessary. To-day the braking is all done from the engine cab, except in yards where, of course, the overhead wires have their normal height of 22 ft. from the rails, permitting safe clearances for manual operation of the brakes.

*Train lighting and heating.* On account of the necessity of wiring for electric heating and lighting some 2500 coaches, it seems reasonable to retain the present method and apparatus of heating and lighting the trains in the electric zone. To accomplish this it was only necessary to supply each electric locomotive with a small steam boiler, used solely for train heating. The Pintsch gas system has been retained intact. Later, when the service is sufficiently extensive, all trains will be heated and lighted by electricity.

All multiple-unit cars are to be heated and lighted by electricity. The problems of heating and lighting a multiple-unit train and a locomotive train are quite different. In the former the current is fed into the train at several points, as many as there are motor cars; in the latter it can be taken only from the locomotive (if there are two locomotive units, of course, it can be supplied from both). Again, in the case of the multiple-unit equipment, the supply of current is along progressive points of the train-length, thereby not requiring train bus-bars of excessive copper section, while in the case of the locomotive train, the supply, whether from one or two units, will be at the head end of the train, thus requiring a transmission of considerable length. A train of 12 cars, for instance, would be between 700 and 800 ft. long. Allowing 24 kw., maximum, for heat and light per car, would require the delivery of about 300 kw. apparent power. An investigation of this department in electrification has brought out some interesting details, particularly in reference to locomotive transformer design and electric car jumpers.

*Fatalities.* As has been pointed out, we have had several fatal accidents, due to men coming in contact with electrified wires. We are none the less concerned that in every instance they were men employed by the company. In each instance the accident was due to carelessness or violation of instructions, and most of the accidents occurred during the period of construction. The operating period has provided a smaller number of these unfortunate events, and the records to-day now seem to indicate that the future will be free from this most regrettable feature.

*Cross-catenary versus bridge-bents.* The excellent results of a year's experience with cross-catenary construction in our Port Chester yard, Fig. 13, where as many as ten tracks are spanned, is tempting encouragement for its application to main-line work. Should the cross-catenary be used, anchor bridges should be spaced at close intervals, say one per mile. The question of the use of cross-catenary versus the bridge-bent on multitrack roads, however, depends largely upon the right-of-way conditions. Cross-catenary struts have to be guyed. In many instances right-of-way limits will require the guy to be placed on foreign land. If the additional cost of the foreign land brings the catenary bent up to or more than the cost of the bridge-bent it loses its object.

*Single- versus double-catenary construction.* Lack of operating data led the engineers of the New Haven road to take no chances with the overhead construction, and the double catenary was considered the safest. The adoption of single, double, and compound systems of catenary suspension is so intimately and definitely related to the number of tracks, the length of longitudinal spans, and the cost of transverse supporting structures and foundations, that the determining of the most economical type of catenary construction must necessarily include the consideration of these factors, and for this reason simple standardization adapted to all conditions is impossible.

*Single-phase operation.* The New Haven system provides that the volt manufactured in and leaving the doors of the power house, is the same physical volt that knocks at the doors of the locomotives. Thus the line is the single link that unites the power house and the locomotives. All such adjuncts as step-down transformers, synchronous converters, storage-batteries, and low-voltage distributing systems with their necessary attendant complement of help are dispensed with. The Cos Cob power house has the usual number of men for a station of its output, and the locomotives are operated by the electric locomotive engineer with the customary assistant present for emergency. This crew holds good for single- or double-unit trains. An emergency repair train is the guardian of the line, attending to all matters pertaining to its repair and maintenance. Including the night and day crews of the emergency train, the number of men employed to maintain the distribution system is nineteen. This covers about 100 miles of single track, including yards.

*Conclusion*. The writer will not use the conventional method of summing up and making recommendations. The paper has been written with the intent to lay before the members of the American Institute of Electrical Engineers a practical picture of the New Haven single-phase electrification, describing the first suit of clothes it wore and what it is wearing now. He is conscious of the innumerable little points of real interest that time and opportunity have not permitted him to insert here, but he trusts to the discussion to bring them out. The description of the faults and how they were handled will answer for the usual column of recommendations. In concluding, an interesting definition of engineering comes to mind; namely,

> Engineering is the art of making a dollar earn the greatest interest.

The writer has intentionally omitted the discussion of the operating costs of a direct-current versus an alternating-current system; but, bearing in mind the preceding definition, it is his belief that in the electrification of steam roads to-day straight alternating-current traction is the agency through which that title can be earned.

History sustains the undeniable truth that alternating current is the preferred agent for the transfer of electricity where either distance or capacity is involved. A railroad involves both. Granted, therefore, that the alternating-current traction apparatus has received the trade mark of practicability, what further argument does it need in its favor?

In connection with the New Haven electrification I wish to speak of the privilege of association with Mr. E. H. McHenry and Mr. Calvert Townley. Upon Mr. Townley devolved the responsibility of decision as to the form of electrification selected. Neither the object nor the scope of this paper can include a description of the analytical course of procedure preparatory to the conclusion that the New Haven road would adopt the single-phase form of electrification. Suffice it to say that Mr. Townley's conviction to accept this responsibility were sufficiently strong to lay the foundation of this work. To Mr. E. H. McHenry, whose serious illness had prevented his filling the office of vice-president in charge of matters pertaining to engineering, fell upon acession to that office, the responsibility of ratification or disagreement with the policy as set forth by Mr. Townley. That ratification is better written in the details of the electric zone itself, as in each department of power house line and locomotive may be seen the betterments due to his suggestion. To him is due the credit of the practical issue of this electrification.

This paper would indeed be incomplete did I not refer to the splendid courage and indomitable pluck of our contractors, who through a fire of criticism and business depression perseveringly stuck to their belief in the principles they were advocating. They can now have the satisfaction of viewing something begun and something finished; for while there may be many improvements to accrue to the alternating-current, single-phase system, the trunk-line principles have by them been laid and demonstrated.

## DISCUSSION ON "THE LOG OF THE NEW HAVEN ELECTRIFICATION." NEW YORK, DECEMBER 11, 1908

**President Ferguson:** The American Institute of Electrical Engineers is to be congratulated in having as a member, a man who is so willing to come forward and frankly state the actual experience he has had in the construction and operation of so new, so important, and so untried an undertaking. I think we owe it to him to show our appreciation of the work he has done by giving full discussion to his paper: first, as to the major and minor faults that have been experienced in the system and of the corrections that have so far been applied, and of the possible corrections that may come in the future; secondly, as to whether this system, as designed and constructed, will fill the requirements of the entire electrification of the road from New York to Boston, as we understand is contemplated by the railroad; thirdly, as to whether this system as designed and constructed will fill the requirements of the electrification of terminals in our large cities, taking into consideration the handling of the through and suburban passenger traffic as well as the switching and hauling of the freight traffic.

**Calvert Townley:** I am strongly impressed by the extremely radical treatment which the author has given to his subject. Abandoning the usual course of emphasizing the advantages of the system adopted, he has passed over them with but scant mention, and has given in minute detail a list of the troubles encountered. The magnitude of the project itself, the amount of advertising which it has had, and the fact that it has been attacked continuously, not to say viciously, by those who disagreed with the plans adopted, or perhaps were interested in seeing them fail, demonstrates the author's courage in handling the subject as he has, but also emphasizes the radical character of his treatment. What the designing engineer wants to know, what the constructing and the operating engineers want to know—what indeed everybody wants to know who is undertaking a new project is, what troubles and difficulties he is likely to meet, and how can they be overcome. The advantages of one plan or another, the perfect features, so to speak, will, in great measure, take care of themselves. Therefore, where a system is already playing so important a part in the railroad world as is the single-phase system—destined to play a much greater part in the future—we are particularly fortunate in having a member who can present so full a log of its application to so important a project, and of its troubles and their remedies, as Mr. Murray has done in this paper.

It is to be noted that Mr. Murray has omitted the customary statement of conclusions usually drawn from the facts furnished in a paper. The conclusions, however, are none the less clearly indicated, even though they may not be stated. Those which seem to stand forth are:

1. This system was put in without any previous similar installation to pattern after.

2. Several of its fundamental features were either entirely new or had so new an application, that their previous use was not much of a guide.

3. Sundry and various defects developed as the installation progressed, resulting in interruptions to the service.

4. These defects have practically all been remedied, and certain other improvements have been made.

5. Five months after the complete substitution of electricity for steam, and while some of the improvements have still to be completed, the system has been demonstrated to be successful, and well adapted to the service for which it was designed. As an interesting fact it may be here noted, that at the present time the electric service is less subject to interruption than was the steam service which it has replaced.

From an engineering standpoint it may help us to realize the nature of the project undertaken, if I recapitulate some of the pioneer features that were included in this installation. For example: it is the first installation to generate single-phase current in large units at a fairly high electromotive force with a dead ground on one side of the generating system; it is the first installation to adopt, though not the first system to put into operation, the 11,000-volt, alternating-current trolley, with the rail return, without any transformer, converter, or other substation appliance whatever between the generator and the locomotive itself; it is the first alternating-current system to handle 800-ton trains at 60 miles an hour; it is the first installation to use an alternating-current, gearless, 25-cycle motor (it also uses much the larger motors of this type); it is the first installation to adopt a locomotive unit designed to fit the normal, instead of the heaviest, train service, and to take advantage of the multiple-unit feature of operating two or more locomotives together, when heavier trains require it.

In my opinion, the one radical thing that was done wrong in the New Haven electrification, and which was really at the bottom of the major part of the difficulties that have been encountered, is that the electrification was not begun soon enough. It is undoubtedly true that had more time been allowed for attention to the minor details of the equipment, and could work that had to be done under great pressure have taken its normal course, many of the minor troubles which can be traced to these facts would never have existed, and, furthermore, had there been time for a reasonable operating tryout, very many of the defects which have caused delays to service, would have been detected and remedied during the trying out period instead of in practical service.

In referring to the log of operation, Mr. Murray says, "We are not proud of it." I am not one who feels that any apology for the results obtained is in order. The combination of an installation embodying so many new features and an insufficient time in which to overcome difficulties, was recognized in the beginning, and it was felt that a superior plan, handicapped with some temporary troubles, was better than an inferior plan with fewer threatened temporary troubles, but many permanent disabilities.

I should feel that I had been remiss if I closed my remarks without paying tribute to the Westinghouse engineers for their part in this project. Their development of the necessary machinery and appliances alone has made the project possible. Without them this single-phase installation could not have been successful. They are rightfully entitled to a frank acknowledgment of their continued cheerful, resourceful, and courageous coöperation through the entire progress of this enterprise.

The keystone of the system is the locomotive. Without the single-phase, alternating-current motor the whole plan would become impossible. No one doubts but that a power house can be built successfully to generate current, and that a line can be constructed successfully to transmit single-phase alternating current at any reasonable voltage and over a wide range of quantities; but it was not until the single-phase motor was developed, that the simplification possible with this form of traction could be even considered. To me, therefore, the most interesting part of this paper relates to the performance of the locomotives. The log of operation showing delays, etc., is interesting, but I do not regard it as of particular importance from an engineering standpoint, as a hot bearing on a blower motor would as quickly bring about a delay to service as an entire breakdown of the locomotive itself. Some troubles with the minor parts may always be expected at the start in any large installation, but if the fundamentals are not impeached, success is not in jeopardy.

A study of the list of changes that were made in the locomotive originally furnished, and enumerated by Mr. Murray, discloses the interesting fact that while there were a number of electrical difficulties, a very large per cent of the changes made were mechanical, not only mechanical changes to mechanical features, but also mechanical changes to electrical features, most of the latter being on the minor parts of the equipment, which, naturally, had to receive the least attention when time was pressing. With the principal elements of the locomotive design; namely, the large gearless, 25-cycle motors, there has been practically no trouble. Their performance as to torque, commutation, and capacity has been most gratifying. It was soon demonstrated, in fact, that the motors and transformers had capacity for service in excess of that called for by their guarantees, and investigation showed that by somewhat increasing the capacity of some of the minor parts of the locomotive equipment, a machine of materially greater duty would be provided. For this reason several changes were made in the locomotive details, not primarily to correct defects, but so to increase the capacity of the parts modified as to provide an excess locomotive capacity. Mr. Murray mentions but briefly a feature of locomotive design, which from the standpoint of dollars and cents value to the operating road, deserves a place in the front rank. Perhaps he has passed by this feature so readily because his mind has been bent on telling of troubles, and this feature has caused no trouble. I refer to the flexible drive whereby the armature of the gearless motor is wholly supported on, and exerts its driving power through a set of spirally concentric springs. Trackmen have frequently been appalled because electric locomotives are so much harder on track than steam locomotives of even greater weight, and it has now come to be a generally accepted conclusion that this fact is due to increased impact because the armature dead-weight is supported without cushion, rigidly on the axle. The impact due to this additional dead-weight is something astounding. In the New Haven locomotives, the method of mounting the armatures, obtaining the cushioned effect, exerting the full driving power of the motors, and compensating for the so-called varying torque thereof, has been successfully accomplished in a way never before tried. The results in improved track maintenance cannot fail to be of far-reaching consequence.

Similarly with the line—while insulation troubles have been manifest, due first, to low bridge clearances, and secondly to steam locomotive stack discharges, the principal overhead difficulties have been mechanical; that is, the mechanical wear on the trolley wire and too great rigidity in its method of support. The serious line difficulty to which Mr. Murray refers, resulted from a combination of these mechanical troubles. They were not discovered for the first time in May, but had been manifest for a considerable period, and were being carefully studied. The extent of the trouble, however, could only be demonstrated by an extended tryout, because it was affected so vitally by the amount of stack discharge and by the rapidity with which the pantagraph shoes traveled over the trolley wire at high speeds. The addition of a steel wire flexibly suspended from the copper conducting wire, a wire to take the wear, was, however, the solution. With it there disappeared the last threatening difficulty that need cause any apprehension.

**B. G. Lamme:** Though I have been more or less intimately interested in all of the problems in this New Haven electrification, there were two parts of the total equipment to which I gave a great deal of my personal attention, namely, the design of the alternating-current generators in the power house and the main motors on the locomotive. The popular opinion, even among designers, was that the motor was by far the most difficult problem of the two, considering that it was the first large gearless single-phase motor constructed for commercial service. As for the generators, one engineer has said "anyone can build generators." However, from my own point of view, since borne out in practice, the design of the motors was a comparatively simple problem compared with that of the generators.

Considering first the main motors, there are 41 locomotives on this road, each with four gearless motors, wound for both direct-current and single-phase operation. I do not intend to discuss the design of these motors, but simply to indicate some of the records that have been made. In the motors themselves there were two points that were generally looked upon as sources of weakness; namely, the commutation (and life of the commutator) when operated on alternating current, and the use of preventive leads (or so-called " resistance leads "), between the armature winding proper, and the commutator. Many people have sounded a warning in regard to the dangers from the use of these preventive leads. It was also assumed that there would necessarily be severe sparking at the commutators of these motors, which was bound to injure them in a relatively short time. Let us look at the record on these two points:

As I stated, there are 164 main motors. The first equipment was put into commercial service the latter part of July 1907, and the last equipment, being part of the order of six, mentioned by Mr. Murray, was put in operation about July 1908. The records show that the total of 164 motors have averaged slightly over 40,000 miles each since being put in operation, the minimum mileage for any one motor being approximately 28,000. A range from 30,000 to 50,000 miles will cover the record of most of these motors. With the above mileage, the commutators of these motors are all in excellent condition, having a good polish and showing but relatively little wear. Virtually all of the motors on the first 35 locomotives have been dismantled at some time or other, for the causes mentioned in Mr. Murray's list of changes. At such times the commutators of these motors were cleaned up slightly, just as any other part of the motor would be cleaned up. The commutators were not turned unless they showed evidence of mechanical injury, generally from some cause external to the commutator itself. However, in commercial service these commutators have required no attention, and, as far as I could determine, none of them has ever been sand-papered while in service. At the present rate of wear on these commutators, there appears to be 15 to 20 years' life in each one of them. As there is but relatively little sparking, even when developing two or two and a-half times full-load torque, there is no real reason why these commutators should not make such good records.

Considering next the injuries to the motor. Mr. Murray's tables show reference here and there to motor injury, without stating just what kind of injury is meant. Simply to state that a motor is injured, without saying what part is injured, may give a wrong impression. It is generally considered, and correctly so, that an injury to the armature of a motor is a much more serious condition than an injury to the field or the connections. The records of the New Haven installation show that the injuries to the armature represent only a small percentage of the total injuries. In fact, the few damages to the armature have been largely from external causes, foreign substances, such as bolts, tools, water, etc., getting into the motor, or from unsoldering at the commutator or at the rear end, due to the extreme overloading, which has occurred in a few instances, as when pulling a heavy train with one locomotive with one pair of motors cut out. In a few instances these damages have resulted in an actual burn-out of a section of the armature, necessitating part rewinding.

In such cases I have been able to make a thorough examination into the condition of the winding on the armature, both in the main winding and in the preventive-lead winding. These examinations have been very interesting. They indicate clearly that the armature windings are showing no dangerous overheating from the heavy loads that have been carried, and also that the preventive leads are showing no more evidence of heating than the main windings. If any comparison could be drawn, I would say that of the two, the preventive leads were in the better condition. Furthermore, only two instances have been found where there was a breakdown in the preventive lead. In other words, the record for these leads is better than that for the main coils themselves. But this is partly due to the fact that the preventive-lead winding lies underneath the armature winding proper, and is thus mechanically protected to a greater extent than the main coils. From the standpoint of experience then, these leads have proved to be one of the most durable parts of the equipment; taking everything into account, their record may be considered exceptional. If the rest of the New Haven system had shown anything like as good a record, there would have been no occasion for the greater part of Mr. Murray's paper. I think the time has now arrived when the "preventive" leads, as they should more correctly be called, should stand on their own merits, for no amount of criticism can belittle the record which they have made in the New Haven service.

Now consider the generators. No defect has developed in them which was not, to a certain extent, foreseen and apparently provided for, based on the data at hand. However, on the completed machine, the first and most pronounced source of trouble was heating, not in the winding, but in the field or rotor structure, due to the pulsating reaction of the armature winding when carrying a heavy load in single-phase current. This reaction was known previously to building these machines, but on machines of smaller capacity it had not developed destructive tendencies. It was proved later that this was simply because it had not been tried out under the conditions which would develop its most harmful effects. This pulsating armature reaction may be analyzed in the following manner:

Consider the armature winding as a magnetizing coil fixed in the space and carrying an alternating current. This coil may be considered as setting up an alternating field fixed in space. For analysis, this alternating-current field, fixed in space, may be considered as made up of two constant fields of half value, rotating in opposite directions at the synchronous speed of the machine. One of these fields therefore rotates at the same speed and in the same direction as the rotor. The other field is traveling round the rotor core in the direction opposite to its rotation. This field may therefore be considered as equivalent to one fixed in space with the rotor running in it at double speed. This armature, carrying single-phase current, could be replaced by an external direct-current field, and if the rotor were run at double speed in this field, an equivalent result, as regards heating, should be obtained. This core thus becomes an armature core subject to a heavy induction at a high frequency.

When the first rotor was built, the structure was laminated as completely as mechanical conditions would permit. However, in the case of high-speed turbine-generators of very large capacity, it is almost impossible completely to laminate everything, due to the fact that the mechanical requirements call for rigidity in some of the structural features. Upon testing the first machine it was found that there was local heating, with heavy load, sufficient to create hot spots in the core; and in a comparatively short time in turn these hot spots damaged the insulation on the coils from the outside, thus causing grounds on the winding. As soon as this was noticed, an effort was made to eliminate these hot spots; but it was found, after several attempts, that as soon as one was eliminated others would show up in some different place as soon as a higher load condition was reached. It was evident, after considerable work had been done, that the correct remedy was not being applied to this trouble. It was then decided to take a bold step by attempting to eliminate all pulsating reactions from the armature, by putting a short-circuited winding on the rotor, of such value that a very large current could flow in it with but very little loss. It was the idea to damp out the field in very much the same way that the armature of a polyphase alternator will demagnetize, or kill its magnetic field, if the armature terminals are all short-circuited together. It is known that under this condition the armature current will rise to such a value that the field flux is practically eliminated. In order to maintain this condition indefinitely without overheating, it is only necessary to put enough copper on the armature so that the $I^2R$ losses in it under this condition are within the temperature capacity of the windings. Working on this theory, a complete cage winding was placed on one of the rotors of the New Haven generators. This rotor had not been designed originally for this purpose, and it was therefore difficult to adopt the most suitable proportions in this winding, but what was put on, immediately showed in practice that a practicable remedy had been applied for this trouble. Meanwhile the new rotors designed for the application of heavy cage windings were under construction, and upon the installation of these, the field or rotor trouble all disappeared. It is interesting to note that the fourth machine installed, which has a 4260-kilovolt-ampere single-phase rating, has a solid steel core, in the surface of which the copper cage winding is embedded. As this winding completely eliminated the pulsating armature reaction, there was no further occasion for laminating the field as a protection from magnetic pulsations.

I might add that a number of the earlier tests, leading up to the design of the first New Haven rotors, were misleading, in the fact that turbine-generators were used for obtaining the preliminary data for single-phase operation and, in all cases, the machines had solid steel cores. These cores acted as dampers to a certain extent, and this in itself eliminated part of the pulsation. It thus developed afterwards, that in the very act of lamination to avoid the trouble, we had gotten into it deeper.

Practically all this work on the generators was done before the full electric service was established, and while only one or two generators were required to be operated at one time. With one generator running, there was apparently but little or no disturbance due to short-circuits on the system. As the service was increased and two generators put in operation, the effect of short-circuits became more pronounced. When, in June 1908, the entire electric service was established, and three generators were connected to the system, it soon became evident that there was some serious condition existing in the system, as indicated by the extremely violent shocks to everything in case of a short-circuit. This was particularly noticeable in the switching system, and, as Mr. Murray intimates, in the case of a short-circuit, all the switches in the system felt it their duty to jump in and open the circuit. This indicated an abnormal current condition. It was calculated that these machines would give possibly six or seven times full-load current on the first rush, in the case of a dead short-circuit, this excess current dying down to possibly two or three times normal full-load current. All indications were, however, that this current was being greatly exceeded, and therefore a series of oscillograph tests were made to determine the current rush when the lines were purposely short-circuited under various conditions. These tests indicated that under certain conditions each machine could give, at the moment of short-circuit, almost 5000 amperes on one phase, the normal full-load current being 340. With three machines in parallel, this would therefore mean that approximately 15,000 amperes could be delivered momentarily. This enormous current rush was sufficient to explain many of the difficulties, but this was not all the explanation. The oscillograph tests also showed that this short-circuit current would be maintained at almost its maximum value for a very considerable period, due to the cage winding on the rotors of the generators. Apparently this current at the first rush, was not appreciably greater than that on the machine before the dampers were added, but without the dampers the field was killed more quickly by this enormous current, so quickly that apparently the breakers did not open until the current had fallen somewhat. However, with the heavy cage winding on the field structure, secondary currents were set up in this winding, tending to maintain the field strength, and thus the current rush was maintained at almost full value for possibly 20 to 30 alternations. These oscillograph tests indicated very clearly that the armatures of these generators did not have nearly so great internal self-induction as our calculations indicated.

Meanwhile, the generators in the power house had been suffering from the tremendous shocks which accompanied short-circuits on the line. There is necessarily considerable local field around the end-windings of all these machines, and this stray field is especially large on machines with a small number of poles, and, in consequence, high ampere-turns per pole. These stray fields at the ends tend to exert a bending or distorting effect on the end-windings. In any given machine the distorting force varies as the square of the current carried by the coils. Our experience with the windings on these machines indicated that they were being subjected to enormous forces in the end-windings. The oscillograph tests gave an indication as to the amount of this force. As the machines could give about 15 times full-load current momentarily on short-circuit, the force acting on these end windings would be 225 times normal; in this case, therefore, these forces were so great that it became a serious problem to devise a type of bracing on the end-windings sufficient to withstand such a force. It should also be borne in mind that probably as many short-circuits came, in one day, on these generators, as the ordinary high-voltage, power-house generator is called upon to sustain in one year. While ninety-nine shocks out of a hundred might not be sufficient to do damage, yet if the shocks occur frequently enough, the hundredth one will soon be reached. In our endeavors to support these windings against movement, probably the most complete system of bracing ever applied to alternating-current generators was developed and used on these machines.

But in spite of this there was evidence of movement at times. It thus became evident that some method of limiting this short-circuit current to the value originally intended; namely, about six times full-load current, would have to be applied. This was done by placing an unsaturated choke-coil, or impedance coil, on the trolley side of each machine. This coil takes up a comparatively small voltage under normal operation, but in case of a short-circuit, the electromotive force generated in it is sufficient to limit the current rush to less than half the value it would attain without this coil. Thus as the shock on the end windings of the generators varies as the square of the current, it is evident that cutting this current in half would cut the shock to one-quarter of its former value, which, with the method of bracing used on these machines, would mean the difference between good and bad.

When these choke-coils were installed, the results on the power house were evident. The shocks on the machines were very greatly reduced, so reduced that we do not fear future trouble from this source. It is interesting to note that No. 4 machine; that is, the 4260-kilovolt-ampere generator, referred to before, was put in service a considerable time before the choke-coils were installed, and it went through the most severe short-circuits ever encountered on this system. Its armature winding has never shown any distress. This is partly because, in the design of this machine, the difficulties to be overcome were known, and the remedies could be applied in the most suitable manner.

An interesting point in connection with the use of the cage windings on these generators, is that the apparent regulation of the system has been improved. This was anticipated, but the actual result in practice was more pronounced than was expected. In installing new rotors for these machines with the heavier cage dampers, the inherent regulation of the generators was made somewhat poorer than before, partly in order to accommodate certain structural features in the rotor. It was anticipated that the cage winding with its damping effect would, to a certain extent, mask this poor regulation by making the machine sluggish as regards fluctuation in voltage with sudden variations in load. In practice it was found that, with the later rotors with their poorer inherent regulation, the average regulation of the system was considerably better than before, thus indicating that most of the disturbances in the voltage, when the old rotors were used, were due to sudden changes in load, while the slow variations were taken care of by the automatic regulators. With the new rotors the voltage changes are so slow, that the Tirrill regulator has plenty of time to act before any serious disturbance can take place.

It must be borne in mind that in one way this New Haven power-house installation was more difficult than anything undertaken heretofore, and that is, in the use of 11,000-volt generators with one terminal connected directly to ground. Taking this condition into account, together with the enormous current rushes with consequent shocks on the winding, and the single-phase operation of units of such large capacity, it may reasonably be claimed that this was the most difficult case of alternating-current generation ever undertaken.

**L. B. Stillwell:** The writer of the paper is just emerging from a long and most trying contest with difficulties upon a conspicuous stage. The installation for which he is largely responsible did not attain, during several months of initial operation, that degree of reliability which the traveling public has a right to expect, and, naturally, it has been subjected to severe criticism. It is probably as a result of this criticism that Mr. Murray's paper is so constructed as to convey an exaggerated idea of the shortcomings of the system, while it fails perhaps to emphasize sufficiently the far-reaching importance of the fact that the single-phase alternating-current system is in actual service in the operation of this very important terminal and that this operation is successful. Its success is shown by a reduction in aggregate train delays when the present service is compared with the steam service which it has replaced.

Papers which set forth fully and frankly not only successful achievements but also mistakes, are of especial value, and all who appreciate the difficulties which beset the path of progress, and particularly members of this Institute who, by training and experience, are qualified to form well-grounded and just opinions, owe it to the officials and engineers, who have laid before us these valuable data, to regard and discuss the facts judicially and without prejudice, and to interpret them fairly to the railway world and the general public. I am sure we shall all endeavor to do this, but I trust that a cautionary suggestion will not be regarded as irrelevant, for the Institute is under exceptional obligations for this paper, not only to Mr. Murray but to the officers of the New Haven Railroad Company who have authorized its publication, for an opportunity to weigh and utilize operating data of a kind not often published.

The engineering world is fortunate in the fact that the New York Central Railroad and the New Haven Railroad have not adopted the same electric system. Such an opportunity to compare the possibilities and limitations of the direct-current system and the single-phase alternating-current system is unprecedented, and, except in America, would be impossible. Whatever we may think of the wisdom, from an economic standpoint, of investing millions to learn from experience, the answers to questions which by German methods, for example, might be answered at much less cost (and there is much to be said on both sides of this question) we as engineers are in no position to complain of lack of opportunity to subject our ideas to the test of practice. If, therefore, we fail to agree with reasonable promptness upon fundamental specifications of that system of electric equipment, which we shall advocate as a standard in railroad practice to be kept in view and ultimately used to the exclusion of the many possible but less desirable alternatives, we shall never see electricity applied in the operation of railroads to anything like the extent which its possibilities justify from an economic standpoint. Unquestionably, each and every problem of electrification should be studied primarily with reference to local conditions and requirements. In any given case it is conceivable that such local conditions and requirements may properly lead to the adoption of a system other than that which would be chosen to solve the more general problem of electrifying not only a terminal and limited suburban zone, but a railroad division or a trunk line. But we are all convinced that during the next ten years railway electrification will not be limited to terminals and suburban operation, within narrowly restricted zones. In this light the decision of the New Haven officials to adopt, in the equipment of its New York terminal, a system applicable not only to terminals but also to trunk line operation, and the frank presentation of results attained, should assist powerfully in the prompt evolution of that system which is fittest, and therefore destined to survive.

When Mr. F. J. Sprague, with clear conviction and admirable courage, installed the multiple-unit system of train operation on the Southside road in Chicago, a most important advance was made in the art of railroading. The applicability of this system to trains requiring tractive efforts exceeding 50,000 lb., was demonstrated first in the New York Subway. The equipment of the New York Central has contributed to our demonstrated utilities an excellent third-rail construction. Incidentally it has demonstrated most effectively, throughout the steam-railway world, the fact that under the conditions existing within the zone electrified, electricity can do the work of steam and do it better.

The New Haven installation, substituting 11,000 volts for 600 volts and eliminating sub-stations, opens the door to possibilities of electrification of railways, with its assured improvement of service and economy of operation, over zones far beyond the reach of the 600-volt direct current.

Under the conditions of respective development of the direct-current system and the single-phase alternating-current system, the decision of the New Haven management to use the system adopted was a bold one; and its boldness was emphasized by the selection of the highest standard voltage for which suitable alternators had been constructed.

With reference to the plan adopted to improve the overhead trolley construction which converts this to a catenary construction with secondary suspension cable, I observed in Hamburg recently that the single-phase system in use in that city employs this method of supporting the trolley wire.

In electric operation of railroads the three great links of the chain between coal pile and draw-bar are the power house, the locomotive, and the system employed to transmit power from power house to locomotive. The power house and its equipment as constructed for alternating-current operation is practically identical with that constructed for direct-current operation. The only differences are that one phase is transmitted instead of three phases, and that one side of the circuit is grounded. The fact that the New Haven road has experienced an unusual number of delays, due to power-house trouble, is due to errors in the design of the generators and in the high-potential circuit-breakers. It seems that these errors could have been avoided by the exercise of that degree of care and foresight which an installation of such importance should receive. Of the ten electrical failures which occurred from July 1 to October 31, 1908, and involved delays exceeding 300 train-minutes in each case, eight were due, as Mr. Murray says, "to simultaneous failures of several circuit-breakers due to a short-circuit." This apparently might and should have been prevented by previous investigation of the ability of the circuit-breakers selected, to function under the conditions of service to which they were applied. Of the other two cases of serious failure, one apparently was due in part to a defective circuit-breaker; the other was a case of locomotive derailment.

So far as four months' operation may be taken as a guide, there is nothing in the record which is discouraging as regards performance of the electric equipment of the locomotives. If we except the delays due to circuit-breaker failures, the record is a good one.

It will add to the value of the paper if Mr. Murray will supply, for purposes of comparison, the record of train delays in steam operation during, say, the corresponding months of the preceding year. It is to be hoped also that the engineers of the New York Central will follow the example set by Mr. Murray and lay before the Institute a log of the New York Central electrification showing results attained as compared with preceding steam practice. This would afford an opportunity for accurate comparison of the results attained by the two contrasted electric systems in the operation of these important properties.

An incidental problem, which at one time appeared rather serious, but which apparently has been solved in an entirely satisfactory manner by the engineers responsible for the equipment of the New Haven Railroad, is the protection of existing telegraph and telephone systems from the effects of induction due to power currents.

Operation thus far has covered too short a period to justify final conclusions in respect of the reliability and safety of the high-potential overhead trolley and feeders, especially as the system has not been called upon to meet the conditions imposed by snow and sleet. If Mr. Murray will supplement his paper six months from now by a contribution giving the log of operation during the coming winter, and if some one representing the New York Central will favor the Institute with similar information, further conclusions of importance can be drawn.

**E. B. Katte:** If Mr. Murray could tell us in some detail of the troubles which led to the failures that caused the delays, it would help to a better understanding of the situation. He mentions two instances where no power was available on the direct-current third-rail. On July 8, the erecting men dropped a signal-mast across two tracks and broke down the third-rails, and there was a delay to trains while getting the third-rail up again. A few days later, on July 10, there was another delay of 13 minutes to the New Haven trains, due to no power on the third-rail. The third-rail was knocked down by a freight wreck, and there was some delay to traffic in clearing the tracks and in building up the rail. I think I can say that at no time has there ever been a lack of direct-current power available to apply to the third-rail when the third-rail was standing, and further, that when the third-rail has been knocked down due to a derailment or a wreck, it has been our usual experience that the third-rail has been re-erected and ready for service as soon as the wreck had been cleared and the track rails made ready for traffic.

**H. P. Davis:** In the operation of a railroad one condition stands ahead of all others; namely, the trains must be kept running and the schedule maintained at almost any cost. In this connection, Mr. Murray has presented, in a most striking way, a condition of vital difference between electric and steam operation of a railroad in the comparison which he has made of the delay chain. The importance of these conditions and the respective bearing of each of the links in this chain have received only slight attention in the literature of railroad electrification, but to those engaged in this work, it has been recognized as of vital importance, for the success of any large electrification is predicated wholly upon the infallibility of each link of this chain.

The usefulness of the electric locomotive is only realized with continuous and unfailing source of current supply. Realizing this, the working out of the problems presented in the power house, and particularly in the feeder and trolley system, are the most important presented to-day for our consideration.

As Mr. Murray points out, none of the separate links of this chain presents new principles, but when moulded together, some very astonishing characteristics have developed in the combination, when applied on a railroad system like the New Haven.

One of the preceding speakers has discussed most admirably the problems presented in the power house. It is my belief, however, that insurance in this respect really resolves itself into the question of sufficient reserve capacity. The really troublesome member of the chain is the link between the power house and the locomotive. The answer to the question: what is the best way to distribute current at high potential to a trolley wire over a busy railroad, with four or more parallel tracks, increased in places to several times this number, and connected at intervals to busy sidings and shifting yards?—is yet to be forthcoming.

For economy of conductors and high efficiency in transmission, the New Haven system will be hard to improve on. For in this system the 11,000-volt generators are connected directly to the line without the use of intermediate apparatus, thus eliminating all losses due to apparatus of this kind. The question whether it is the best for continuity of service and for operation with a minimum of train delays in case of trouble, time only will tell and is now, of course, open to argument and discussion.

The troubles encountered with the New Haven distributing and trolley system can be divided into two classes.

1. Those which have been constructional.
2. Those which have been a matter of operation.

Difficulties in the constructional features of the New Haven line have occurred, as pointed out by Mr. Murray. I look on this, however, as an unavoidable penalty, consequent to any pioneering installation, resulting from lack of knowledge and inability from previous experience correctly to forecast the conditions to be met.

It must be admitted that the problems encountered on this railroad are not simple, nor within the scope of ordinary or established practice. Many conditions have arisen impossible to foresee and guard against. It is only by encountering these difficulties that experience can be gained and data obtained to correct the constructional faults. Constructional difficulties, so long as they are not fundamental, do not affect the delay chain except to the degree of time sufficient to investigate the troubles and provide means to correct and eliminate them. The flexibility of the distributing and trolley system in operation is, however, of crucial and lasting importance in the delay chain.

Under the subject, "Distribution," Mr. Murray uses the word "disadvantages" in referring to this system. He should have used the word "difficulties." These have now been largely cleared up and have been shown to be only incident to a complete knowledge of what has been taking place in the system. In the last sentence of the paragraph above referred to, Mr. Murray says: "This operation can be effected, and at the time of this writing an effort is being made to obtain these results in practice." Since the preparation of his paper, most satisfactory results have been obtained with the scheme which has been developed, and as it introduces something new and likely to become general practice in power distribution, I shall briefly describe it.

Fig. 5, is a diagrammatic representation of the scheme of the New Haven trolley and feeder connections. By reference to this it can be seen that if selective operation of the circuit-breakers installed at each end of a trolley section can be obtained, in case of trouble in the section only the length of single track in that section will be affected. No delay to trains will occur, as they can be shunted on one of the adjacent tracks, except in case of not more than a single train, which might be in the section at the time of trouble. In principle this closely approximates the more advantageous feature possessed by the steam unit in confining delays to individual trains in case of trouble. Attention is particularly called to this to show that careful thought was given to this feature of the problem in planning the installation, and that its importance was recognized.

In practice, the failure of the line to operate as laid out was for a considerable time extremely puzzling. The destructive action of short-circuits on the circuit-breaking apparatus, on the generator windings, on the insulation of the line, and the failure of the circuit-breakers to be selective, could not be explained by any previous experience. A careful and thorough study of the nature of these disturbances by means of the oscillograph showed current surges of great severity, both as regards amount of current supply and the duration of the surge. It was shown, for instance, that with three generators connected to the line, it was possible for them to deliver at times as much as 120,000 to 150,000 kilovolt-amperes single-phase, and to maintain it for a period approximating one second.

It is not surprising, that circuit-breaking apparatus set for instantaneous operation failed, and that it was not selective in action, for the automatic trips on the trolley breakers were set to act at currents so low as to be out of all comparison with the amount supplied, and as the feeder and trolley arrangement is a series-parallel one, there was more than enough current in the distributing system to trip them all over the line. It was apparent, as soon as it was realized what the trouble was, that:

1. The generators must be provided with some sort of a shock absorber to protect against the first rush of current at times of short-circuit.
2. The opening of the circuit during times of heavy current surges must be prevented, because of the possibility of violent voltage surges from such operation with resulting destructive effect on the insulation of the system.
3. The current supply in the distributing system on short-circuit must be controlled, and automatic operation of circuit-breaking apparatus must be prevented until this condition was established.
4. The line sections must be made selective.
5. Corrective apparatus should be simple and automatic.

To meet the first condition, choke-coils were placed in the trolley phase of each generator, the coil being permanently in circuit. This coil is designed to cut down the maximum short-circuit current values to about 40 per cent, and the resulting mechanical shock to about 16 per cent.

To limit the current to be opened in the distribution system, and to make the selective action possible, was a more complicated problem and has been solved in the following manner.

Ohmic resistances have been placed in each of the three feeder leads going to the distributing system. These resistances are normally short-circuited by circuit-breakers. These circuit-breakers are electrically operated, and are automatic in opening and closing, being controlled by a single underload and overload master relay, so installed that the entire station single-phase output passes through it. The automatic tripping coils of the circuit-breakers on the overhead feeder and trolley systems are normally cut out; in other words, these circuit-breakers are normally non-automatic; the automatic operation being controlled from the power house.

In the event of a short-circuit or overload on the system exceeding a certain predetermined current, the master relay above referred to operates, causing the circuit-breakers short-circuiting the resistances to open. The resistance is thus automatically inserted in the feeder circuits. The value of this resistance is sufficient to reduce the current to a certain fixed and predetermined value. As soon as the resistances have been inserted in the feeder circuits, a feeder wire connected with all of the trolley and feeder circuit-breakers is then automatically supplied with potential. This at once makes the circuit-breakers automatic throughout the feeder and trolley system.

Each of the trolley sections terminates at anchor bridges. These bridges serve the double purpose of anchorages for the trolley structure and of sub-stations for current distribution to the adjacent trolley sections. Current is fed from the power house to the bus-bars on these bridges by feeders supplemented by the entire trolley system. The whole distributing system is, therefore, multiplied at each anchor bridge. Each end of a trolley section connects to the bridge bus-bar through a single circuit-breaker. In case of a short-circuit in a section, it is evident that these two circuit-breakers will have the total current flowing divided between them. As the remainder of the system is in multiple with the bridge bus-bars, these two circuit-breakers will be carrying much more current than any others.

With this circuit condition established, it is only necessary that the power-house resistance shall be so proportioned that it will allow sufficient current to flow to trip the two circuit-breakers in the trouble section, and yet limit the amount of current to less than enough to trip any of those in parallel in the remainder of the system.

With the current reduced to this definite amount, it divides through the system properly, concentrating at the point of trouble. The amount of current is, as pointed out, less than the amount required to operate any of the circuit-breakers, except those adjacent to the point of trouble. As soon as these two breakers open, the troublesome section is disconnected, and the current in the power house will at once drop to normal value. When this happens, the master relay at the power house will act again, and cause the circuit-breakers shunting the resistance to close and short-circuit it. At the same time, the feeder wire connecting to the automatic trips on the circuit-breakers of the trolley system will be opened, thus leaving the whole outside system again non-automatic. This entire cycle is accomplished automatically (without the use of delicate or complicated apparatus), power never being removed from the line. The whole cycle takes only about two seconds.

If it happens that one or both of the circuit-breakers at the ends of a trolley section fail for any reason to operate, and thus do not clear the line, it is arranged that the main circuit-breakers at the power house will operate and open the entire circuit. To accomplish this, the main power-house circuit-breakers are provided with time relays of the constant time type, set so that they will not act until a sufficient period has elapsed for the trolley and feeder current breakers to open. This condition is, however, of rare occurrence.

The use of a scheme of this kind, in which ohmic resistance is thrown in series with the distributing system at the first rush of current to a short-circuit, has other advantages beside that of making the system selective; for it effectually prevents much line disturbance directly traceable to violent opening of heavy currents by circuit-breakers, and to making circuit again under these conditions. As the trolley and feeder circuit-breakers are normally disconnected, the circuit cannot be opened at the first rush of current. The resistance being inserted in circuit first, the current is lowered to a value which is sufficient to trip only the circuit-breakers on each end of the trouble section.

When the circuit-breaker does act, it is called to open a practically non-inductive circuit, so that voltage surges cannot be produced, thus safeguarding the insulation of the system. For the same reason when power is thrown on the line the resistances act to damp out any surging effect. This arrangement provides a method of limiting line disturbances; for no matter how severe the short-circuit, or how great the amount of power available in the generating station, the circuit-breaking apparatus cannot act under conditions which will destroy them or cause destructive effects in any part of the system. It also has the advantages of being entirely automatic in action and effectually overcomes, without service interruption, effect of flashes, which are common in a system like the New Haven. In a case of this kind, when no permanent ground exists, the automatic insertion of the resistance into the line will usually cause the flash to be extinguished without interruption of service and without harmful effect. This method is simple, automatic in action, and most effective in controlling and regulating destructive line effects, and will, I think, either in this form or in some modification, be used quite generally in future in distributing systems of this kind.

**Philip Torchio:** In the paper, the main cause of the considerable troubles due to circuit-breakers is ascribed to the fact that the type of breaker used had the oil-tank grounded. The author suggests that the lining of these tanks should be improved. I would ask why, in the corrective changes introduced to overcome this deficiency of the circuit-breakers, no consideration was given to the obvious types of circuit-breakers which have the oil-tank insulated from ground. I would also like to ask why, in a single-phase electrification, three-phase generators were used in preference to single-phase generators? Would it not have been preferable to adopt single-phase generators? By using single-phase the company would eliminate, of the numerous generator troubles, those troubles which seem to have caused repeated rebuilding of the field of the generators on account of local heating resulting from the magnetic distortion due to the single-phase load upon three-phase generators. This magnetic distortion would have been considerably less with a single-phase generator.

**C. P. Steinmetz:** The importance of to-night's paper and discussion consists in the explicit and concise information which it gives as to the progress in the development of the electrification of a part of one of the country's trunk lines by means of the single-phase alternating-current motor. It is especially gratifying to see that the statements which have been made by unbiased engineers based upon theoretical considerations, have now been verified by practical experience, and that heavy railroad work can be handled by single-phase, alternating-current motors, though obviously not with the same high drawbar pull per ton of locomotive weight, and, possibly, at least for the present, not with quite the same reliability of service.

This I believe establishes the single-phase alternating-current motor as one of the pieces of apparatus by which the future electrification of our country's railway systems will be accomplished. The drawbar pull per pound of motor weight of the single-phase, alternating-current motor must necessarily be lower than that of the direct-current motor, because in the alternating-current motor the magnetic field pulsates between zero and a maximum. The same motor, when energized by direct current, with the same maximum magnetic flux, would give 41 per cent more output. It is important, therefore, to know that in those cases where direct-current motors cannot be used; for instance, where heavy train units at infrequent intervals traverse long distances, the work can be done by alternating-current motors. I believe when the time arrives to electrify our transcontinental railways, this will be done by means of the alternating-current motor.

My conclusions from the evidence and data now available are the same as I have expressed before; that those railway problems which cannot be handled by direct-current methods must be solved by means of the alternating-current motor. But where direct current can be used equally as well as alternating current, the higher weight efficiency; that is, the greater drawbar pull per pound of motor weight afforded by the direct-current motor, necessarily makes this motor preferable from the electrical engineer's point of view.

It is interesting, then, to observe that in those immediate railway problems which can be handled by alternating-current motors as well as by direct-current motors, the decision whether one or the other type of motor should be used has shifted from the electrical engineer to the railway engineer or the railway manager. This decision will be determined by the economic question whether higher weight efficiency, that is, higher draw-bar pull per pound of motor weight and reliability of service, should be sacrificed because of the possibility, at some future time, when the electrification of railroads for long distances is proposed, of being able to extend the same system of operation over remote parts of the road, and also to other roads where direct current can not be used; or whether the higher weight efficiency of the direct-current motor, and the at present greater reliability of service, compensates for the possibility that at some future time with the advance of the electrical industry and the extension of railroad electrification, we may have to replace the locomotive equipment, or change locomotives at the end of the direct-current zone and the beginning of the alternating-current zone.

**Minor M. Davis** (by letter): It is possible that Mr. Murray's remarks about the effect of single-phase currents upon telegraph and telephone wires will be misunderstood. Transformers are by no means completely corrective, although to some extent they are beneficial. My understanding is that the transformers on the New Haven road are applied only to single-wire operation and that they do not neutralize the disturbing effects of the single-phase electric current sufficiently to permit the operation of duplexes, quadruplexes, and printer circuits upon the wires to which Mr. Murray refers. This means that one-half or two-thirds, or even a larger proportion, of the carrying capacity of the telegraph wires is destroyed, notwithstanding these transformers. To apply these transformers, several otherwise idle wires must be carried upon the poles, and these wires and transformers are objectionable. They complicate single-wire equipment and prevent the operation of multiplex systems. Although Mr. Murray refers to the pilot wires and transformers as " not costly ", they mean considerable expense. It is more or less of an open question, as I understand it, whether it is the duty of a corporation to prevent its electric current interfering with the current of another company, or whether it is the duty of the latter to provide its own protection. I understand the highest court in New York state has ruled in one of its decisions that if a party:

> Collects for pleasure or profit the subtle and imperceptible electric fluid, there would seem to be no great hardship in imposing upon it, or him, the same duty which is exacted of the owner of the accumulated water power: that of providing an artificial conduit for the artificial product, if necessary to prevent injury to others.

Certainly there is no disposition on the part of the telegraph companies to retard in any way the advancement of the art of applying power. They are willing to exercise all reasonable patience, and they would be glad to have the power companies adopt a simple and inexpensive remedy for these disturbances; but although the writer and his associates have given much attention to the subject they know of no remedy which is at the same time simple, inexpensive, and complete.

**B. A. Behrend:** The single-phase generators have been a source of great trouble, the cause of which was not immediately recognized. The heating of the units due to the variation in the armature reaction was overcome by low-resistance circuits placed in the rotor surface, and acting as the secondary winding of a transformer. This winding, however, reduced the effective reactance on sudden short-circuits, resulting in great increase of the momentary short-circuit currents, and in disturbing forces corresponding to the square of these currents on the armature conductors. Both these difficulties were minimized by reactance coils placed in the feeders. I should like to ask Mr. Murray what reasons have prevented the adoption of two-phase generators in the New Haven case, and what are, in his opinion, the objections in general to two-phase generators for this class of service.

The difficulties experienced with the collection of current are not specifically connected with the single-phase system, but they are, at present, an essential part of all systems of electric railroads employing high potential. An inspection of the line and the flashes produced by imperfect contact, which I had an opportunity of making since the steel wire has been installed, indicated that great improvements have been made in that direction.

The difficulties experienced with the single-phase locomotives and the motors in particular, are the vital issue. Through the courtesy of the New Haven road I had the opportunity of observing the motors of a heavy two-engine train between the Grand Central station and Stamford, Conn. The operation on both direct-current and alternating-current power is very much alike, as far as sparking is concerned. In fact, the eight motors operated very well and without undue sparking, both in starting, and at about 65 miles an hour. No unbiased observer of experience with electric-traction apparatus can close his eyes to the fact that, if such results can be obtained in the first large plant of this nature, very much better results may be predicted for the system in the future.

The temperature rise on alternating current is naturally greater than on direct current. It would be extremely interesting to obtain comparative figures from Mr. Murray on this subject. This matter is intimately tied up with the question of efficiency to which Mr. Murray has alluded, without, however, going into figures.

**H. F. Parshall** (by letter): In 1901 I was appointed by the Board of Trade a member of a tribunal, presided over by the Hon. Alfred Lyttleton, to determine whether or not such an alternating-current system as proposed by Ganz was suitable for the underground railways of London. The matter was most thoroughly investigated from every point of view. I came to the conclusion, which conclusion was supported by the umpire, that the alternating-current traction system was not the best for working a heavy passenger service. My reasons were that the alternating-current motor is at serious disadvantage as compared with the direct-current motor during the period of acceleration; that from the nature of things it is inherently heavier and more complicated, and must be more expensive as regards first cost, and vastly more costly to maintain; that the sole advantage incident to the use of an alternating-current motor is in the supposed saving in the first cost of the collector system; that when a high-tension system is safely installed it must be more expensive than a third-rail system—consequently the whole reason for the existence of an alternating-current system disappears in the final result. Since 1901, material progress has been made in the design of alternating-current motors, and the greatest credit is due to those engineers who have brought the alternating-current motor to its present high state of perfection. Nothing, however, has occurred that would justify me in departing from my original conclusion. In the beginning it was suggested that the alternating-current motor would not have a commutator, and that this evil inherent to a direct-current motor would be dispensed with. In the final result, however, a commutator 50 per cent bigger than the direct-current commutator has been found necessary. The perfected alternating-current motor weighs about 40 per cent more, has all the objectionable features of the direct-current motor and practically twice over, on account of the construction of the stator. The air-gap of this motor in practice may not exceed 60 per cent of that of an efficient and well-designed direct-current motor. Higher armature speeds have generally been found necessary. With the features above mentioned inherent to alternating-current motors, the first cost of a train equipment, as also the maintenance, must be nearly double that of a direct-current equipment of like capacity. Further, I doubt in the heaviest class of electric traction installation, such, for instance, as that in the New York Subway, whether the alternating-current motor can be made to do the work satisfactorily at all, over a period of time. In addition to the above well-known features of the alternating-current motor the use of a train transformer has to be considered. What ultimate size and form this transformer may take in heavy, high-speed work remains to be determined, since with a jumping contact the strains on this transformer are practically incalculable.

I think it must be conceded by all, that the alternating-current train equipment, *per se*, is inferior as regards cost and maintenance to a direct-current train equipment, and that it gives no tractive advantage. The advantage, then, must be external to the train, and confined to the system of transmission, or more properly the collector system, since the transmission system would naturally be the same either with direct current or alternating current. As a matter of experience it has been found that the cost of a high-tension overhead system properly installed is greatly in excess of that of a third-rail system, and having regard to the exceedingly numerous difficulties, as put in evidence by Mr. Murray's paper, it cannot be contended that the action of an overhead high-tension system is anything like as satisfactory as the third-rail system. Considering all that has gone on in the New Haven system up to September 5, 1908, which appears to be the termination of Mr. Murray's log, there is absolutely nothing to indicate that during 1909 some such series of occurrences are not again to be expected. All that has occurred may be expected to occur again in some form or another, since electric traction apparatus does not manifest all its faults during the first few months of operation.

The absolute lack of commercial data as regards the cost of the installation, cost of operation, and cost of maintenance vitiates any conclusion that may be drawn other than that the system when compared with such a system as has been installed by the New York Central is entirely unjustified by the practical results. Some two years ago I was shown a diagram of the feeders and electrical system of the New Haven Railroad. I could only state that it transgressed every established principle as to safe and reliable working, and that if the system as a whole were to be in any way justified, there was no excuse for starving the system of feeders to such an extent, and mixing up what might be properly termed the collector system with the transmission system. In my judgment many of the troubles that have been experienced would have been avoided had the alternating-current system been installed in accordance with accepted alternating-current practice, with a high-tension system of transmission, say from 20,000 to 30,000 volts with substations at the different sections and a trolley voltage not exceeding 5,000. The cost need not have been greater, and the system would have been far and away safer, in that the different sections could be independently controlled. Further, the volume of stray current in the earth causing electrolysis and induction troubles would be greatly lessened. The system has apparently been designed on the assumption of the undisputed right to the wholesale use of the earth as the return circuit.

As regards the difficulty experienced with the generators, the New Haven line is not unique in this respect. With a feeder system, however, designed as above, it is doubtful whether the generator windings would have been displaced, although the use of a train transformer and a jumping trolley contact may be expected to introduce unexpected phenomena. Looking at the alternating-current system broadly, it seems to me that its advocates are more interested in the electrical than the mechanical aspects of the electric traction field, and its opponents are those who have had the longest experience in traction matters and are not inclined to experiment with the fundamental elements of a traction system, considering the sole and total advantage that can seriously be suggested is cheapness. Why a railway should spend its tens of thousands per mile endeavoring to make a system as safe as possible, and then attempt to effect a minor saving by the introduction of a system bringing with it fatal and most experimental elements, is beyond my comprehension. Mr. Murray states that there have been no fatalities so far as the public is concerned, nor would one expect such fatalities considering the short time the system has been in operation and the overhauling to which it has been subjected. In the fulness of time, however, there may be collisions, derailments, or some such occurrence, in which the overhead system will be disarranged, at the same time as passengers debouch from the trains. The result of an occurrence of this description will in my judgment sound the death-knell of the alternating-current system so far as a passenger service is concerned. It is stated that there have been several fatal accidents to the employees. The number is not given although I have been informed it is considerable, and in the nature of things it must be so. Men are required to maintain a good train service, and throughout the world it is recognized, sacrifice their safety to the public needs. When, however, an element of certain death so insidious as a system of high-tension conductors is made an accessible and working part of a railway system, nothing but a long list of fatalities can be expected. No amount of rules and regulations will ever suffice to make a system, having inherent fatal elements, safe to the employees, in fact, having regard to the exigencies occurring in normal railway practice, rules and regulations in general may be taken as existing in form and not in substance.

I regret to have to make use of Mr. Murray's expression in stating as my conclusion that his paper furnishes conclusive material of how not to install a traction equipment, and it appears to me the only way he could possibly justify his belief as regards the commercial usefulness of the system would be by the publication of such commercial data as would show that the alternating-current system as regards first cost and cost of operation has such material advantages over the direct-current system that all such occurrences as are recited in this paper are as nothing considering the proved commercial advantages.

To summarize, I may say I am responsible for the electric traction installation of the Central London Railway. While this was one of the first systems to employ multiphase transmission with synchronous converters and a direct-current collector system, none of the troubles instanced by Mr. Murray has been experienced, and since the installation opened there has never been, all told, an hour's delay caused by any electrical failure; in fact the whole service has been characterized by the utmost regularity and freedom from trouble either electrical or mechanical. Since the installation was designed, considerable improvement has been made in motors, so that with the interpole construction higher voltages are practical. Also with the under-running protected third-rail system these higher voltages can be safely employed without risk either to the public or to the staff of the company. Having regard to the history as regards reliability and freedom from trouble with a third-rail system, as also the wider field over which it is applicable on account of the above improvements, I am of the opinion, so far as the working of passenger services over the widest districts is concerned, that the direct-current system of electric traction is superior to the alternating-current system for dense traffic movements, and in the majority of cases in which electricity can properly compete with steam. That there are problems in connection with freight haulage over long distances in which the multiphase system possesses commercial advantages, I do not feel in a position to deny, although an examination of the individual cases which have been submitted to me has not in my judgment made this an indisputable fact. As regards the single-phase, alternating-current system there may be special applications to which it is commercially applicable. I have given the deepest study and thought to various problems, but in each case the use of the single-phase system has proved illusory. I do not wish to go further than to state that I have not found a problem to which it is properly applicable, considering all the facts as I now see them. I have recently pretty thoroughly investigated railway matters in the United States and, considering the inherent properties of the different classes of apparatus, my conclusion is that the direct-current system of electric traction is superior to all others, and is likely to remain so for many years to come.

**A. H. Armstrong:** The enthusiastic coöperation of the engineers of the railroad company and the manufacturing company has brought this alternating-current installation to its present engineering success, and nothing but admiration can be expressed for the courage and ingenuity shown in overcoming the difficulties met with in operation.

It is my understanding that the alternating-current single-phase system was adopted in the New Haven installation in order to afford an opportunity to demonstrate the suitability of that system to the possible further electrification of the road. It is further my understanding that preference was given the system chosen, for the reason that it was considered to be a cheaper system as to first cost than either the 600 or the 1200 volt direct-current systems, proposals upon which were also received.

As pointed out in the paper, the overcoming of difficulty after difficulty met with in operation, is positive proof of the progress made in perfecting the complete electrical and mechanical equipment. Material changes have been made both in the construction of the locomotives as well as in the generating and distributing system, so that the final installation as now in operation is widely different from the original plans, both as to engineering details as well as to first cost of the apparatus finally installed. Certain changes were made in the generators, in the switchboard controlling apparatus, etc., in order to obtain increased capacity and reliability, these changes presumably resulting in a somewhat increased cost over that of the original plans.

The trolley construction as now installed embodies certain improvements, as pointed out in the paper. A considerable departure must have been made from the original plans in order to account for the large difference in the estimated cost of this part of the installation, before and after its completion. In the December issue of the *Street Railway Journal*, 1905, Mr. Westinghouse publishes his estimate of $12,436 per mile as sufficient to cover the cost of contact line on a four-track road between Woodlawn and Stamford. Presumably this figure covers the same labor and material, estimated to have actually cost nearly $55,000 by Mr. Wilgus in his paper before the American Society of Civil Engineers. In view of the wide discrepancy between the cost of the trolley construction as proposed, and as completed, it would be instructive to know which of the two figures is nearer the actual construction costs.

The locomotive changes found necessary are most frankly stated by Mr. Murray. They have been extensive, and those listed are presumably the changes after the original locomotives were received, and developed defects in practical operation. The author also states that the locomotives have fulfilled their guarantees as to their capacity to haul 200 tons trailing. A log of the run giving the time required to haul 200 tons trailing with 45-second stops averaging 0.451 per mile would have been most interesting. If the present locomotives fulfil the guarantees as to performance of a 26 miles per hr. schedule with a 15 per cent margin in time, it may account for the increase in locomotive weight from 68 tons total, as proposed, to 102 tons as now in operation.

It is reasonable to suppose that the cost of these locomotive units has increased in at least a like ratio, although it is my experience that it costs considerably more to construct an alternating-current single-phase locomotive than one of equal weight equipped with direct-current motors. We are therefore impressed with the fact that in this completed New Haven alternating-current installation many changes have been found necessary, not only in the apparatus as originally furnished, but also in the original plans upon which the decision to adopt alternating-current motors was presumably based.

Published figures of trolley construction indicate that this item was estimated at but one-fourth the actual cost, while the increase in locomotive weight would account for at least an increase of 50 per cent in the cost presumably used in the original estimates. The large increase in cost of these two items may be accounted for, either by an error in the original estimates, or by the assumption that continued development of the alternating-current single-phase system has called for more liberal construction, greater factors of safety, and a readjustment of ideas previously formed.

While preference may originally have been given the alternating-current motor for this installation, with the limited knowledge of its operation then considered, I find it hard to justify Mr. Murray's present enthusiasm for a system that appears to be in many ways unsuited to the New Haven conditions. In this connection, I will state that the weight of the locomotives as now installed approaches fairly close to the weight of the locomotive which I estimated was required to perform the service originally specified.

No operating company can afford to submit to the traffic interruptions and delays outlined in Mr. Murray's paper, unless the object to be attained be of the most far-reaching character. In view of the fact that the alternating-current trolley construction as installed on the New Haven apparently costs 80 per cent more than a 600-volt third rail, and the alternating-current locomotives cost at least double for the same service performed, it is instructive to compare the operating results secured with the two systems.

COMPARATIVE DATA ALTERNATING-CURRENT AND DIRECT-CURRENT LOCOMOTIVES

| | 600 volt d.c. | New Haven<br>11,000 volt a.c.<br>600 volt d.c. |
|---|---|---|
| Weight total | 94.5 tons | 102 tons |
| Weight on driver | 68.5 " | 77 " |
| Number of motors | 4 | 4 |
| Total h.p., 1 hr. rating | 2200 | 1000 |
| Guaranteed trailing load | 400 tons | 200 tons |

The locomotive weights given above, include pony trucks on both locomotives.

Having approximately the same total weight, a single New York Central locomotive unit has a capacity equal to two New Haven units, although the motors of the latter are cooled by forced ventilation, while in the New York Central motors natural ventilation is employed.

Much has been said to-night about the New Haven locomotives meeting their guarantees, and handling a trailing load of 200 tons, and also the wisdom of not adopting a unit of any larger capacity on account of the average weight of trains on the New Haven road being approximately 212 tons. I have drawn up a list of the trains drawn on November 21 by the New York Central locomotive unit, a single unit. This list comprises a majority of the trains handled that day which exceeded the guaranteed trailing load of 400 tons.

NEW YORK CENTRAL LOCOMOTIVE PERFORMANCE

Trailing Loads in Excess of 400 tons, Nov. 21, 1908

| Train No. | Weight | Train No. | Weight |
|---|---|---|---|
| Special | 475 tons | 7 | 480 tons |
| " | 570 " | 71 | 471 " |
| 54 | 416 " | Special | 571 " |
| 14 | 430 " | " | 424 " |
| 18 | 424 " | " | 558 " |
| 28 | 434 " | " | 483 " |
| 26 | 491 " | " | 420 " |
| 16 | 468 " | " | 475 " |
| 10 | 445 " | " | 506 " |
| 58 | 628 " | " | 482 " |
| 22 | 411 " | " | 460 " |
| 23 | 467 " | " | 550 " |
| 27 | 441 " | " | 572 " |
| 31 | 524 " | " | 536 " |
| 17 | 439 " | " | 558 " |
| 33 | 475 " | " | 570 " |
| 9 | 454 " | " | 575 " |
| 19 | 668 " | " | 571 " |
| 3 | 515 " | " | 650 " |
| 41 | 465 " | " | 519 " |
| 29 | 541 " | " | 600 " |
| 59 | 516 " | " | 560 " |
| 37 | 420 " | " | 569 " |

It is to be noted that every one of the above trains hauled by a single direct-current New York Central unit would have required two New Haven alternating-current units.

The reliability of the direct-current and alternating-current system is clearly illustrated in the following table of train-minutes delay for the months of July to October 1908, inclusive. The alternating-current figures are taken from Mr. Murray's paper and the direct-current figures from the New York Central operation. The figures for the New York Central operation are not official, but doubtless Mr. Murray can correct any error with his possible access to official records.

TRAIN-MINUTE DELAYS, CENTRAL AND NEW HAVEN, 4 MONTHS, JULY-OCTOBER, 1908

| | New York Central | New Haven |
|---|---|---|
| July | 41 | 2281 |
| August | 53 | 1611 |
| September | 18 | 893 |
| October | 48 | 910 |
| Total | 160 min. | 5695 min. |

The New Haven figures make no note of delays of over 300 minutes. The Central figures include delays due to locomotives or operators only, as during these four months there were no delays due to generating, transmission, sub-stations or third rail and feeder distribution systems, in spite of the alleged complication of such a system.

It is difficult to assign any exact field for alternating-current motors, but it is my conviction that under the conditions outlined in Mr. Murray's paper, the installation of the alternating-current system is a mistake, and that Mr. Murray has not shown any reason for his statement that if three years ago he was in favor of the alternating-current system for the conditions outlined, he is much more in favor of it to-day. In view of the fact that the generating station does not cost less, that the overhead trolley construction costs 50 per cent more than a third-rail construction, that the locomotives cost fully double that of corresponding direct-current locomotives of the same capacity, it is hard to find any justification for the enthusiasm displayed for the alternating-current system installed under the conditions outlined in the paper.

**N. W. Storer:** In his remarks, Mr. Armstrong makes comparisons between the New York Central and New Haven locomotives. A table is given in which the weight of the New York Central locomotive is stated to be 94.5 tons, while that of the New Haven locomotive is given as 102 tons. Following this table is the statement that the locomotive weights given include pony trucks on both locomotives. As to the exact weight of the present New York Central locomotive, I am unable to give any information, except that it has usually been given as about 97 tons, instead of 94.5. However, it is well known, and has been announced in the technical press that all the New York Central locomotives are to be reconstructed by changing the two-wheel trucks to four-wheel trucks, and that the weight of the modified locomotive is between 115 and 120 tons. Of course, as the New Haven locomotives have been modified so much faster than those on the New York Central, their weight may be temporarily slightly in excess of the New York Central locomotives, but, to be strictly fair in the comparisons, Mr. Armstrong should have given the final weight of the locomotives.

Mr. Armstrong also states in his table that the guaranteed trailing load of the New York Central locomotive is 400 tons, and that of the New Haven is 200 tons. The trailing loads of these two locomotives should, of course, be compared in the same kind of service. The New York Central guarantee was based on express service with long layovers. The New Haven locomotive was guaranteed to handle a 200-ton trailing load in *continuous local service*. These locomotives are guaranteed to handle 250 tons in local service as far out as Port Chester, a distance of 25.6 miles from Grand Central station. They also handle 300 tons trailing load in local service to New Rochelle, a distance of 16.6 miles. In express service, which is the class of service on which the New York Central guarantee was based, the New Haven locomotive handles easily a load of 300 tons.

In Mr. Armstrong's table, therefore, there should be substituted a weight of not less than 115 tons as the weight of the New York Central locomotive, and 300 tons as the guaranteed trailing load of the New Haven locomotive.

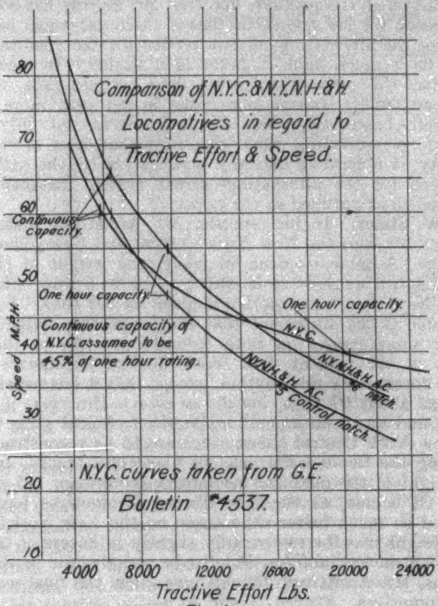

Fig. 1.

No one is more anxious than I to give the New York Central locomotive full credit. I believe that it is doing most excellent service. But what is the service? Simply switching—nothing more or less. There are a few trains that have to be hauled out to Wakefield, a distance of about 12 or 13 miles. The remainder of the trains are changed at High Bridge, which gives a distance of only about 6 miles for the locomotives to handle the majority of the trains. This is anything but trunk-line service. The distance is so short, and the service necessarily so intermittent, that the locomotives should be able to work at a load far in excess of the one-hour rating without overheating. They are, therefore, able to handle the heavy trains without double-heading, as was intended when the electric zone was laid out. It is a noteworthy fact that since the wreck of the Brewster express, these locomotives have never been run double-headed. It is also noteworthy that after that date the limiting speed on the New York Central electric zone was 45 miles per hr. until recently, when it has been raised to 50 miles per hr. Under these circumstances, it is impossible to make comparisons between them and the New Haven locomotives, which are and have been operating in all classes of service, running most of the time at very high speeds. If the New York Central locomotives should be reconstructed so as to make them safe for high-speed express service, and the company carries the electrification to the limits originally considered, there may be a chance to compare the two locomotives on a fair basis. At present to talk about the enormous trailing loads handled by the New York Central locomotives is misleading.

Mr. Armstrong mentions the great increase in weight of the New Haven locomotive over what he thinks was the original estimate. He is in error in regard to this point. The original estimate for this locomotive was 78 tons. The first one built weighed 89 tons. The electrical equipment installed in the first locomotive weighed 10 or 15 per cent more than the estimate, and has been increased very little since then. The additional weight which has been put into these locomotives has been almost entirely in mechanical parts, steam heaters, etc. One thing must be borne in mind: the electric locomotive of the future will be designed so as to have good riding qualities, and to secure them, the mechanical parts will form a much larger part of the total weight than was thought necessary or desirable two or three years ago. This feature in itself will bring the weights of the single-phase and direct-current locomotives much nearer together.

When discussing the question of cost, why is it that the increase in cost of the New Haven installation over and above the supposed estimates is so much under discussion, while in the New York Central installation nothing is considered except the cost of locomotives, and possibly that of a straight section of third-rail. I should be more than glad to see the total official cost of the New York Central installation side by side with that of the New Haven. Without such figures, it is useless to discuss costs. However, it may be noted in passing that the statement of Mr. Wilgus in a paper read before the American Society of Civil Engineers, that the cost of electric current must be increased from 0.58c. per kilowatt-hour at the power house to 2.6c. at the shoes of the locomotive to cover the cost of operation, investment, etc., foreshadows some enormous expenses.

Concerning double-heading, much has been said about the number of extra locomotives required for the New Haven Railroad, on account of being obliged to operate 25 per cent of their trains with two locomotives. In this connection, a query arises in my mind. Why is it that the New York Central finds it necessary to buy 12 additional locomotives, making 47 in all, while the New Haven Railroad can get along with 41 locomotives of such an extremely small capacity as they are supposed to have, in handling all of their traffic as far as Stamford, it being borne in mind, of course, that the New York Central operates a large number of multiple-unit trains. Let us have some actual figures in regard to the New York Central installation, both in regard to cost of installation, cost of operation of power stations, sub-stations, distributing system, etc., and in regard to the mileages, etc., of their locomotives.

**O. S. Lyford, Jr.** (by letter): In developing its plans for electrification, the Erie Railroad Company has adopted the method advocated by one of the speakers. It commenced its work on a moderate scale on a branch line with 34 miles of track and 6 motor cars. This may seem at first to be insignificant compared with the New Haven system; but the mileage is 30 per cent of that of the New Haven, the number of motive power units 15 per cent, and the capacity of each motive power unit 40 per cent. The line is operated with 11,000-volt, single-phase trolley. It was constructed during the operation of the road by steam locomotives, and the division is now being operated by both steam and electric motive power. This line has been in operation 18 months with the following results:

*Safety.* One man lost his life during the first few days of operation by coming in contact with the trolley wire. This was an employee who had been carefully instructed but "forgot." There have been no other personal injuries to employees or to the public due to the electrical equipment.

*Reliability.* In October 1908 there were no detentions chargeable to the electrical equipment. In November there were four detentions of this character: one due to control trouble, two due to hot motor bearings, one due to breakage of air-compressor crank shaft. Three of these detentions were of a character preventable by more rigid inspection.

In December there had been no detentions up to the date of the meeting.

It should be noted that only one detention was due to a strictly electrical cause, and none was due to high voltage or to the single-phase features of the equipment.

It is believed that this record of nearly 2.5 months will compare favorably with any other electrically operated road. This record, however, was obtained only after the equipment had been in process of "tuning up" for many months. In the 12 months ending Oct. 31, 1908, there were 120 detentions chargeable to the electrical equipment, which detentions totaled 4800 minutes. These include a number of serious detentions due to the 90-mile, 60,000-volt transmission line over which power is received from Niagara Falls for the operation of this road. The record is much better than that of the steam equipment replaced.

*Maintenance.* There have been no transformer troubles, either on the cars or in the sub-stations. Motor troubles have been very few. There were no mechanical troubles with the contact wire. The wear on this wire up to August 1908 was from 0.004 to 0.009 in., at which rate it would be between 20 and 30 years before the wire would be worn back to the supporting clips. Stretch of the copper wire and abnormal wear at hard spots will no doubt result in a life materially less than this.

There has been no apparent deterioration of the galvanizing of the messenger cable and other galvanized parts, but such painting as was done on the overhead work has not lasted.

There have been no material troubles or expense caused by locomotive gases.

The life of the pantagraph shoes average about 15,000 miles.

*Cost of operation.* The operating cost under the usual transportation and maintenance headings of the Interstate Commerce Commission classification, averaged during last summer about 18 cents per car-mile.

It is difficult to make a fair comparison of the New Haven log of operations with a similar log of other existing electrical service. The records of such roads as come under the writer's observation vary widely, and the variations are largely due to conditions independent of the character of the equipment.

Multiple-unit service with trains of more than two motor cars shows up better than single-unit service, owing to the fact that many of the faults of car equipment can occur without causing detentions, the other equipment carrying the train through on time.

Some schedules are operated under conditions well within the speed limit of the equipment, so that time can be made up after a detention. On other roads the schedule is practically up to the speed limit.

In some schedules there is considerable layover of trains at one or both ends of the line, while in others, where the conditions permit and the equipment is worked hard, the layovers are short, and a car trouble cannot be remedied in time to prevent delays possibly affecting a number of trains.

If trains are operated on short headway, the train in trouble may be helped through by a succeeding train, thus minimizing the number of train-minutes delay, whereas with infrequent service a comparatively insignificant car trouble may show up badly in the log.

Equipment troubles increase with the speed, particularly troubles with the moving contact.

In an analysis of the troubles which actually occur in electrical operation, whether direct current or alternating current, it is apparent that the power station, transmission lines, substations, and distribution system, whether third-rail or overhead, cause but a small proportion of the train detentions. The record of the third-rail is especially good in this particular. Most of the detentions are due to trouble on the cars, and of these by far the largest proportion results from defective control.

In the light of this experience, it is believed by the writer that the New Haven troubles will soon be confined mainly to the locomotives, and these will not be serious. The forced use of the combined alternating-current and direct-current systems is an abnormal burden on this operation. In view of the fact above stated, that is, that most of the train detentions are caused by the control, it may be anticipated that the New Haven operation will not do quite as well in the long run as a straight single-phase service. The use of multiple-unit motor cars will help to improve the log.

The Erie record above quoted, gives no indication that detentions due to locomotive troubles with a straight single-phase system will be materially greater than with the direct-current system.

The maintenance cost is another matter. The greatly increased cost of the electrical equipment of the locomotive or motor-car must necessarily involve greater cost of repair and maintenance. The savings effected in other parts of the system must carry this burden.

**W. N. Smith** (by letter): The oral discussion of Mr. Murray's paper was so far given over to the particular merits of single-phase railway apparatus, and especially to contrasts between alternating-current and direct-current locomotives, that certain other equally important features of the paper were overlooked.

It was stated that the single-phase motor is the keystone of the system, and controversy upon this feature has been plentiful. The writer submits, however, that although the single-phase motor may figuratively be called the keystone of the single-wire, high-voltage trolley system, the whole system is a means to an end, the end being the minimum cost of motive power which it is possible to effect by means of this system of working conductors.

Comparing the relative amount of dependence placed upon each element of the electric motive power system as a whole, in the last analysis the chief element is the working conductor. In another sense also the working conductor is the fundamental point of departure in a railway system; for in the nature of things it is the means whereby power is supplied to a moving load through a moving contact, instead of to a stationary load as in all other varieties of electric power application. Of the three links in the chain, therefore, the one that is most truly characteristic of railway conditions is the working conductor.

The writer believes it will be conceded by all engineers who have had to carry any real responsibility for bringing a railway line into operative condition, and keeping it there, that the worst interruptions they have to guard against are those due to failures of the working conductors and the power distributing system. That part of the system which is housed in power house and sub-stations, while equally vital in importance with the line, is nearly always present in duplicate, so that failure of one piece of apparatus is quickly made good by substitution, and it is also always possible to duplicate the feeder distribution system; but working conductors, whether trolley or third-rail, are rarely installed in duplicate, and their failure usually means cessation of service until the defect can be reached and repaired.

An examination of the four months' record given by Mr. Murray, as well as records of several other heavy electric traction systems, both alternating and direct-current, show clearly that while the greatest number of train detentions is due to trouble with car apparatus, the detentions due to line trouble or other derangements of the power system are of far greater average duration than those due to car failures.

It is stated by Mr. Murray that it became evident at one time that electrical operation would cease if some change in the contact wire were not effected; but nowhere in the paper is it implied that such a result was at any time impending, by reason of the defects in locomotives or generators. It is difficult to see how greater emphasis could be placed on the necessity for any single element.

As between the merits of the alternating-current and direct-current systems for any given train service on a given road, there is no longer any doubt as to the possibility of determining in advance which system can be installed and operated for the least money; but, with respect to other considerations than those of cost, it is fortunate that engineers now have available the results of the New Haven Railroad experience to assist their judgment in solving heavy traction problems.

Reference has been made to the boldness of the New Haven Railroad in trying such a newly developed system on so large a scale. In the writer's opinion the boldest part of the enterprise was the adoption of a previously undeveloped system of line construction. Unlike the other links in the chain, this one could not be put out of commission for days at a time nor could it be taken into a shop over night and brought out in the morning. It had to be maintained *in situ* over a very frequent traffic and repaired only with the current off, and for the most part from a work train. The engineers who maintained the line in the face of all adverse conditions should be credited with the performance of a task which, however easy to conceive and calculate in advance, was the most difficult to carry out of any, in the maintenance of the whole system.

The means adopted by the New Haven engineers to overcome trolley difficulties seem to have been successful. There is no doubt that the conditions of catenary trolley operation on the New Haven road are so severe, particularly by reason of the frequency of very low bridges, that the fact that there is now a reasonable certainty of continuous operation bodes well for the permanency of the improved methods adopted. Experience on other single-phase systems where traffic and clearance conditions are less exacting, shows that the devices composing the system of working conductors and moving contacts are adequate and reasonably reliable. For railway systems where clearance conditions are severe, and requirements for continuity of service are the most exacting, it is probable that further improvement in mechanical detail of the working conductors and moving contact device will be developed to ensure even greater smoothness of operation. The improvements which experience has shown to be necessary in the manufactured apparatus comprised in single-phase generating and locomotive equipment, seem to have been well taken care of; but the apparently simpler yet more fundamental problem, of improving the moving contact system, still presents a field for the exercise of inventive genius.

**Philip Dawson** (by letter): On broad principles I agree with the conclusions at which Mr. Murray arrives, in which he pins his faith for general railway electrification, of urban, suburban, and long-distance lines, to the single-phase system. It is the very serious inconvenience possessed by the direct-current, third-rail system which I believe has brought about the introduction of the single-phase system. Had it not been for the latter system, the conditions are such that the directors and officers of the London, Brighton, and South Coast Railway Company could never have seen their way to adopt electric traction, if adopting it had involved the use of the third-rail system.

The form of construction is the double catenary, details of which are shown in Fig. 1. Figs. 2, and 3 illustrate the trolley wire after it has been put up and whilst it is only temporarily supported, before being finally fixed to the clips and droppers which support it from the two catenaries. The droppers are solid sherrardized steel wire, the shorter ones having a loop at each end, the longer ones consisting of two parts looped in the middle. This arrangement gives great flexibility for the trolley wire in the vertical plane, whilst ensuring great stability in the horizontal plane.

The catenaries are of galvanized steel wire cable $\frac{3}{8}$ in. in diameter. Each catenary is independently fixed by means of a turn-buckle and insulator, and supported from a saddle-piece resting on the top of the main insulator. The sag in the catenaries is calculated so as to produce absolute balancing at the supports. The principal insulator has to bear a dead weight which amounts to 850 lb.

All of the insulators are of the best quality porcelain. All of them have been tested, the principal ones to 65,000 volts, and the secondary ones to 25,000 volts for 30 minutes; 10 per cent of the insulators were tested mechanically. The whole construction of the catenaries, girder bridges, insulators, etc., is calculated so as to result in a factor of safety of ten.

The trolley wire itself is round, with sharp grooves at the sides into which mechanical clips fix, and its area is 0.197 sq. in.; its tensile strength being in all cases superior to 22 English tons, per square inch. (1 ton = 2240 lb.)

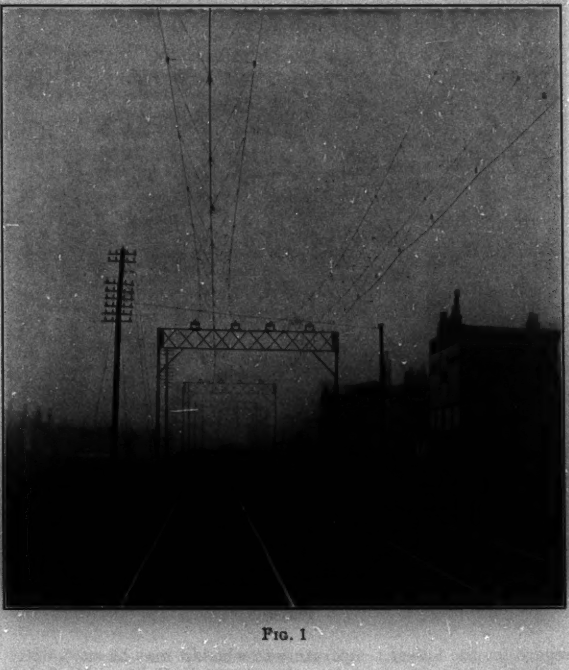

FIG. 1

In order to prevent the hammer blows from which the New Haven line has suffered, the whole construction has been designed so as to make the clips and the droppers from which the clips are supported as light as possible in comparison to the weight of the trolley wire itself.

Three years ago, at the time the London, Brighton and South Coast Railway installation was planned, I made the most careful investigation; and it was then that I decided on the flexible system instead of the rigid one originally adopted by the New Haven line.

The greatest span so far is 195 ft. The vertical projection of the sag of the catenary wire at 50 degrees fahr. for this span, corresponds to 6 ft. Contrary to continental practice, the trolley wire is drawn up and anchored at both ends with due regard for the lowest temperature to which it may be subjected, so that in the coldest weather the elastic limit should not be exceeded in the wire.

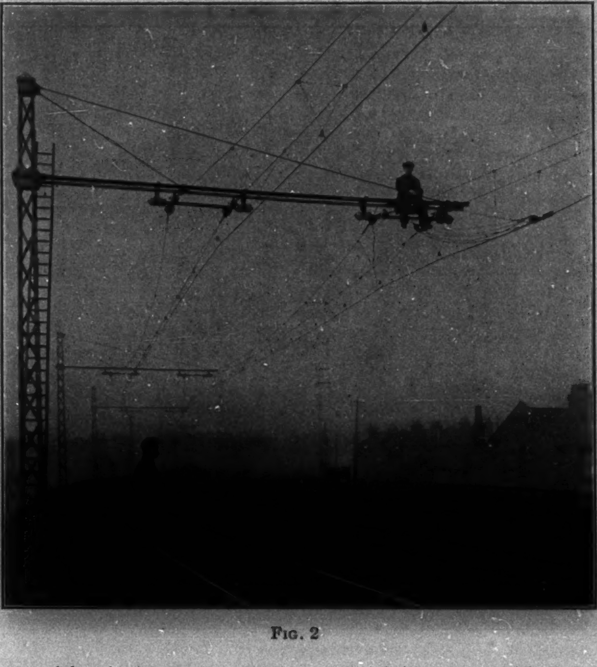

FIG. 2

I have provided for the wire being staggered 18 in. altogether, or 9 in. on either side of the center line of the track, although there are occasions when I have diverted so as to go as far as 13 in. from the center line.

The normal height of the wire will be between 16 and 17 ft., whilst in the two terminal stations the height is 21 ft. At some of the lowest bridges the wire descends to a height of 13 ft. 10 in., or only 4 in. above loading gauge. The train service which will operate over this line at present is of a purely local character, and it is not likely that at the outset a speed of 45 miles an hour will be exceeded.

The extensions that will be proceeded with as soon as satisfactory results are obtained on the first portion now nearing completion may, however, involve the operation, not only of multiple-unit local trains, but of trains hauled by electric locomotives, which of course may obtain speeds considerably higher than that at present contemplated.

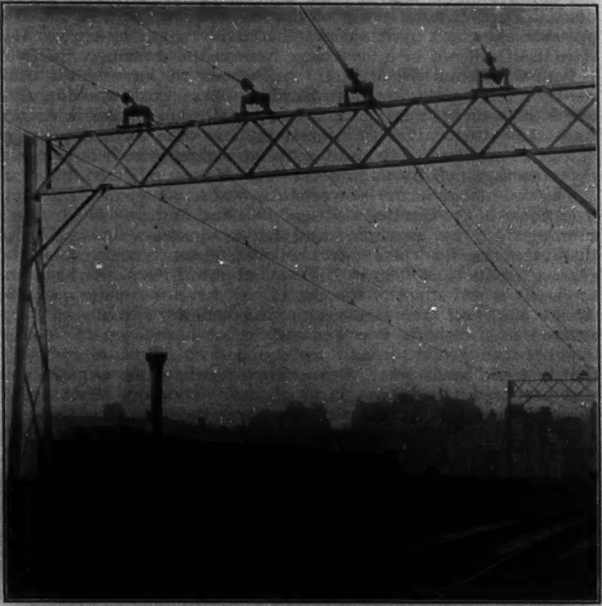

Fig. 3

Careful consideration has led me not to adopt the pantograph type of collector, but to adopt a type of trailing bow collector. This collector consists of a tubular frame, the top of which is fitted with two bows, one forming the rigid portion of the frame itself whilst the other is hinged and sprung from it. It is believed that this method will ensure sparkless running, and operating with a pressure of from 12 to 15 lb. between the collector strip and the contact wire. There are two bows, one for operating in each direction. On the top of the collector bows are fixed renewable grooved aluminum strips, as it is believed that by this means the wear of the wire will be localized on the contact strip, virtually no wear of the trolley wire taking place. Furthermore, owing to the form of strip, and to the low pressure exercised by it against the trolley wire, the cost of the strip itself will not be a very large item in the working expenses.

**Ivan Ofverholm** (by letter): In Sweden we have had a trial road for testing single-phase details. These trials are now finished and a report made, which I hope will soon appear in American translation. It may interest the Institute to read of some details about our trials, and make a comparison between the experience gained by us and the New Haven officials.

The conditions in our power station were somewhat different from those in the Cos Cob station. We had four-pole generators, running 750 rev. per min. and driven by steam-turbines. In this case the fly-wheel effect of the steam turbine with its gearing (reduction 8500 to 750) was about three times as great as the fly-wheel effect of the generator; therefore, when a short-circuit came on, the stresses on the generator shafts were so severe that the shafts were twisted. For this reason the coupling between generator and turbine had to be made so weak that it would break when severe short-circuits came on. It was also proposed to make a kind of spring-coupling that would allow the generator to slow down when the momentary stress of a short-circuit came on; but as the cost of such a contrivance was considerable, we preferred to make a coupling that did break, but was easily replaced.

In the power station there were two generators but only one circuit-breaker, which at the same time kept the generators in parallel and connected to the line. With this circuit-breaker we have not had the least trouble.

In the beginning there was much trouble with the windings of the generators. They were often short-circuited. At first we thought this was due to some kind of high-potential stresses, and put in protective devices. As these did not seem to work at all, we studied the conditions more closely and found that the coils of the windings were bent in many places. We therefore got the idea that the short-circuits were due partly to mechanical stresses. We put in mechanically stronger insulation in some places where weak points were found; since then we have had no short-circuits in the generators, although there have been several very severe external short-circuits.

It interests me to hear that Mr. Murray thinks the single catenary contact line is just as good or even better than the double catenary. In Sweden we think that a contact line without any catenary is the best, provided the mechanical stress in the contact wire is kept constant at different temperatures, and the bow pressure so adjusted that the resultant stress in the contact wire (the sum of the normal stress in the contact wire and the bending stress resulting from the bow pressure) never exceeds the elastic limit. At present it is not so with ordinary trolley lines. In nearly all the cases we have considered, we have found that the elastic limit is exceeded; the fact that the trolley lines do not come down more often, is due to the fact that copper wire can stand bending above the elastic limit to a remarkable degree.

For steel wire the elastic limit is sufficiently high, and according to our researches such a wire can keep the internal stresses sufficiently constant at varying temperature without being readjusted. For this reason I think it was a good idea to put up a steel wire as contact wire on the New Haven road, but I wonder if it can stand the smoke from the locomotives. Our experience in this respect is that steel wire cannot withstand smoke. I know of at least one big installation with steel catenary wires, where these have had to be replaced by bronze wires.

As I have said, we think we can improve the present trolley line construction without catenary very much by using automatically operated tightening gear. We intend to make the distance between the suspension-points 25 to 30 metres. But we do not think that we can operate locomotives at high speeds on such a line with only one bow. It is our intention to use two bows placed 6 metres or more apart. The bow has a small (30 cm. high) top bow with little energy, supported by a pantograph. The arrangement we intend to use is an improved form of this bow.

Mr. Murray says that the insulators for supporting the messenger cables had to be doubled up. As far as I can see from Fig. 13 in the paper, these double insulators are placed in parallel. I know of other cases where insulators had to be doubled up, but there they were placed in series. I know from experience that this does not improve the conditions very much. The arrangement on the New Haven road is, I think, just the thing to be used, as that is the only reliable way by which a bad insulator can be put out of service by itself.

Mr. Murray also speaks of hard spots in the line, and the way to get rid of such things. We have had about the same experience, and therefore we will now make the line as movable as possible in a vertical direction, but have it anchored duly in a horizontal direction.

We don't intend to use any deflectors on our lines. We have made many trials in order to see how to get rid of the difficulties at the points where the wires are crossing each other, and have found that all these difficulties can be done away with by placing the wires in the proper position at the crossing.

As to the telegraph and telephone disturbances, which Mr. Murray says can be done away with by means of pilot-wires and series transformers, in the case of the New Haven Railroad the disturbances seem to be due chiefly to electromagnetic influence and not to the static charging effect from which our telegraph and telephone suffered so much. This can also be helped, but by other means, mentioned in Mr. Dahlander's report on the Swedish trials.

**C. E. Eveleth** (by letter): In explaining the failure of the oil circuit-breakers on the New Haven feeders, Mr. Lamme says that the short-circuit current of the generators reached for a few cycles a value of fifteen times normal, which was far in excess of the amount anticipated. Just why this was not anticipated is rather difficult to understand, as machines giving fifteen times normal current, or even twenty times normal current on short-circuit, are not infrequent; in fact, generators that give less than twelve times normal current for the first few cycles when short-circuited are rather the exception.

The oil switch has been generally regarded as a simple piece of electrical apparatus that can be built in almost any form, and still do its work satisfactorily, but experience shows that for successful design and application there must be at hand quantitative knowledge of the conditions to be met.

When associated with Mr. E. M. Hewlett in the spring of 1902 we were impressed with the evidence of enormous current rushes for the first few cycles when generators were short-circuited, and realized that these conditions should be analyzed if we expected to apply protective devices properly. Subsequently we investigated the magnitude of these effects and the action of oil-switches under short-circuit conditions in a series of tests involving several thousand dead short-circuits at various potentials. from 2200 to 75,000 volts, with and without transformers, transmission lines, etc. With the data so obtained we were put in position both to design switches of great energy rupturing capacity and to select the size and type suitable for specific requirements. In some instances this results in a rather more expensive switch than would be advocated by those who have not had such data at hand, and it is not surprising that they continually run into unexpected difficulties.

Simultaneously with the oil-switch tests, investigations were conducted concerning the requirements of reinforcement of the end-windings of generators. It may be interesting to know that in a number of instances we short-circuited individual generators at full excitation from one hundred to three hundred times.

In 1904 it was my privilege to build and test an oil circuit-breaker—which, by the way, did not have a grounded can, and contained less than three gallons of oil—that opened repeatedly on a single break current of 20,000 to 25,000 amperes at 2200 volts. This was equivalent to a rupturing capacity with four breaks in series, such as would ordinarily be used for a single-phase circuit of over 100,000 kilovolt-amperes. Under these conditions the circuit was ruptured without throwing oil or otherwise damaging the switch, except for some burning of the contacts. As these tests preceded by a considerable time the selection of the New Haven oil circuit-breakers, and as there are many oil circuit-breakers in service for feeders where the total generator capacity connected to the bus-bar exceeds 50,000 kw. it is apparent that circuit-breakers capable of handling the New Haven conditions had been built and might have been selected. If they had been adopted a large proportion of the serious delays would have been obviated.

The accompanying oscillogram shows the action on one of the short-circuit tests referred to. Attention should be given to the lower curve of Fig. 1, which shows a rise to more than double potential in the voltage of the phase not short-circuited. As this potential strain would be applied to all of the polyphase apparatus on the system, and furthermore as there exist at all times badly unbalanced voltages whenever one phase is loaded more than another, especially with inductive load, and the voltage maintained by regulator on the loaded phase, there are some manifest disadvantages in trying to operate single-phase and polyphase apparatus from the same generator. For this reason it is my opinion that such operation is at a decided disadvantage as compared with straight single-phase operation on an undertaking of the magnitude of the New Haven system. I think it would have been better to supply separate polyphase generators for operation of shops and direct-current sub-stations.

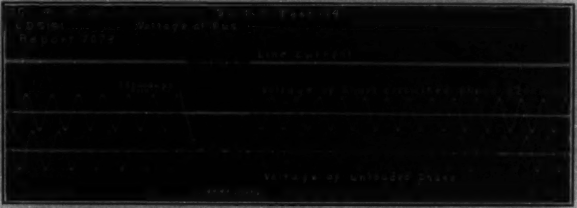

FIG. 1

**W. S. Murray:*** In connection with the discussion contributed by Mr. Townley, it is a pleasure to record the number of interesting points that he has brought out which the paper did not include. As I have been accused of being over-enthusiastic about the New Haven electrification by one author of a discussion, and Mr. Townley has seen fit to feel that I am not sufficiently proud of it, between the two I am able to average a happy medium. As a matter of fact, my pride was inclusive of being willing to make a complete exposition of the difficulties, and in reviewing the paper, while recalling the many successes that could have been mentioned to offset the temporary failures, my mind constantly dwelt on the belief that " our friends ", who were so freely disporting themselves in the general condemnation of the system, were entitled to the actual facts of the situation. In this " deed of gift " I constantly steeled myself against introducing any ameliorating features of success in the system, for fear some slight prejudice would come to their minds. Indeed, I will never be quite able to determine whether the cause of the sudden secession of this voluble condemnation was due to their possession of these facts, or the reliability of train schedule on the New Haven system, which arrived about the same time.

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* The closure of the discussion was written about four months subsequent to the date of the paper.

In reference to the discussion of Mr. H. P. Davis. I am exceedingly glad that he has included so much detail in regard to the general operation of the distribution system. The fear of giving the paper too great length constantly suggested caution in digressing too far from the trunk-line principles involved, and as stated in the closing paragraphs, it was the author's hope that the details of construction and operation would be brought out by the discussion. Mr. Davis has brought out clearly the electrical and mechanical operating characteristics of the distribution system, and it may be said that except for the fact that the multiple arrangement of overhead wires in the distributing system brought about such an exceedingly high conductivity, the circuit-breakers would have functioned entirely in accordance with their anticipated plan of operation. The lowering of the current density on the occasion of short-circuits by the actuation of the auxiliary apparatus described by Mr. Davis has accomplished the degree of selectiveness which was the first aim in the conception of the system.

In connection with this type of distribution system, employing a voltage of 11,000, this is an opportune time and place to point to a suggestion that comes from the mouth of experience. While I do not think it is by any means impossible to design generators of the voltage and capacity, as installed in Cos Cob station, to withstand the shocks of short-circuits of the character that have been received by that station, the form of protective apparatus that has been installed to alleviate the electrical and mechanical strains incident to these short-circuits, certainly suggests the wise expedient of designing a low-voltage station (say not greater than 2300 volts) employing static transformers to secure the higher transmission voltages. It is to be noted in connection with the softening effect, as a result of the transformers being between the generators and the line, that the increased cost, due to transformer equipment, will be offset by a lower price per kw. of generators and switchboards, due to lower voltage and, further, that what loss may be suffered in virtue of the introduction of transformers will be greatly offset by the higher efficiency accruing from a low-voltage, instead of a high-voltage, generating system. I believe in connection with single-phase electrification, this arrangement in power house design should be effected.

Referring to Mr. Torchio's discussion and in answer to his three questions:

1. Concerning the grounded circuit-breaker frame. If the frames of the circuit-breakers were supported upon insulators, this would approximate the ordinary or ungrounded system conditions; that is, where no phases are grounded. But the earth not being an insulator, and as the frame of the circuit-breaker rests on metal (anchor) bridges, as explained in the paper, this brings one terminal of the generating system directly to the circuit-breaker frame; hence, the necessity of strong *lining* insulation. If the frames of the circuit-breakers were ungrounded, this would introduce danger in handling the switches; as it is not impossible to conceive of a connection being made between one of the switch points within the tank, and the iron tank itself, should an attendant be standing on the ground and touch the tank, he would be shocked. By the present arrangement of grounded circuit-breaker tanks this hazard is obviated.

2. Three-phase generators are used in order that power may be supplied to the polyphase motors operating in our power house and in shops adjacent to the line. Polyphase current will also be used in operating direct-current railway plants, whose prime movers, at present, are steam engines, which will, later, be replaced by polyphase motors.

3. Concerning the regulation of single-phase *vs.* 3-phase generators, it is quite evident that the use of single-phase generators would do away with the unbalanced conditions that obtain in the case of the 3-phase generation. However, the amount of unbalancing is extremely small, due to the copper-clad rotors on the generators, and, further, had single-phase generators been used this would not have permitted the advantages of power house, shop and railway plant drive, as described above.

In connection with the interesting discussion that Dr. Steinmetz has contributed, it is pleasing, indeed, to note his prediction that when the time arrives to electrify our transcontinental railways, the alternating-current single-phase motor will be the ways and means. His commentary on weight efficiency suggests a thought which I would venture supplementary to his reference to drawbar pull *vs.* weight of motor. I think it is wise to guard against the exclusive rather than the inclusive view. Given two terminals, say, 12 miles apart, between which electrified tracks are to handle a given traffic, if the fixed charges and operating expenses per ton mile are the same for either the alternating or direct-current systems, it is undeniably true that we can not escape the conclusion that the direct-current type of motor, on account of its lesser weight per pound of drawbar pull, would be the legitimate and logical selection of motive power, or in other words, all other considerations of the system being equated, these and only these are the circumstances under which the matter of weight efficiency is a ruling factor. Where we are considering 50 or 100 miles of dense trunk line operation, the weight efficiency, though having a bearing, takes its position along with the other considerations, but is assigned a proper degree, which becomes exceedingly minor in the consideration of heavy mileages and heavy power requirements. In charging up the alternating-current motor with more weight per drawbar pull than the direct-current motor, the difference can be represented in dollars and cents, but we must not end the investigation where it has just begun. The 12-mile railroad, above described, may have its power station at its center, and its traffic sufficiently light to require no rotary sub-stations, and possibly not very much copper in its distributing system. The situation takes on an entirely different hue, however, in making a decision upon the 50 or 100-mile heavy traffic proposition. If direct-current propulsion is to be used, this will require sub-stations and with it many pounds of low-voltage copper feeder. These items of sub-stations and feeder copper, like the increased weight of the alternating-current motor over the direct-current motor, cost money and must not be forgotten, and so when we formulate weight efficiency equations, while we are not forgetting to charge up the cost of the greater weight for the alternating-current motor, let us not forget to charge up the cost of the copper and sub-stations complementary to the direct-current installation. Outside of all this comes the careful consideration of the system's commercial efficiency, better stated as the ratio of operating expense to gross income and, therefore, except that weight efficiency be considered inclusive and charged with its relative value of importance in the system as a whole, its importance is only apparent and not real.

In reference to Mr. Minor M. Davis's contribution concerning the effect of single-phase currents upon telegraph and telephone wires, I would further supplement my remarks which I made on this subject on the occasion of its reading before the Institute, and say that it was the effort of the author to touch as briefly as possible upon the electrification, in its relations to matters other than traction. Each one of the subjects mentioned is one upon which much interesting matter, in detail, could be brought out, and in this effort at brevity I was conscious of the fact that this particularly important subject might have been treated in greater length. Too much credit cannot be given to the companies adjacent to our property, who were affected by our lines, for their coöperation in which both their efforts and our own were united to overcome the disturbance. As I review the two paragraphs upon this subject, I do not see any occasion to modify the statements that have been made, except to say that possibly Mr, Davis's position enables him to better judge of the cost of the transforming equipment necessary to effect the voltage compensation described.

Mr. Lamme is the father of a practical single-phase motor, and has brought to himself another responsibility in the nature of the dampened field 3-phase generator, which has been so well described in his discussion. However, as progenitor of these two types of apparatus, only the greatest satisfaction can come to him, in view of the uniform good behavior of both, thus making the new responsibilities at once both heavy and light. I am particularly indebted to him for the generous detail in which he has described both of these types of apparatus. Four months have elapsed since his discussion was written, and the short-circuit disturbances that occurred in the generators then described have since disappeared, and the mileages of the motors, instead of the figures as stated by Mr. Lamme, have become in some instances as high as 70,000 miles, the average mileage of all motors being probably 60,000 miles, and this with 60 per cent of the commutators still unturned. As a matter of fact, and as Mr. Behrend has pointed out, the operation on both alternating and direct-current power is very much alike as far as sparking is concerned, and as the number of miles over which a commutator operates before it is necessary to place it in the lathe for turning, is dependent almost entirely upon the degree of fineness with which it commutates, and as the mileage, as stated, is comparable with the ordinary direct-current practice, it is fair to assume that it is a matter of indifference whether the motor is commutating alternating or direct current. Mr. Lamme's interesting statements in regard to the strains produced in the coils of the Cos Cob generators on the occasion of short-circuits, leads me again to one of the fundamental reasons for the low-voltage generating station with step-up transformers. It cannot be denied that a short-circuit on a system of high conductivity produces an enormous rush of current. As previously mentioned, the interposition of the transformers between the line and generators offers a cushioning effect for this blow. Added to this valuable adjunct of protection, is the fact that in the low-voltage-wound generators the coils naturally increase in cross-section in proportion to the ratio of diminished voltage; that is, for the same output and the same number and length of coils, a generator of 2300 volts would be wound with coils whose cross-section would be 4.75 times the cross-section of the coils of an 11,000-volt generator. Thus the coil itself is inherently a strong mechanical device for resisting these strains, and, further, its tendency to puncture is greatly reduced on account of a reduction in potential between copper and iron in the ratio of 4.75 to 1.

In connection with Mr. Stillwell's reference to errors in generator and circuit-breaker design, I think Mr. Townley's statement that the " . . . one radical thing that was done wrong in the New Haven electrification, and which was really at the bottom of a large part of the difficulties that have been encountered is that the electrification was not begun soon enough ", is a complete and decisive answer on this commentary. Seldom, if ever, do we see the manufacturer test at the factory, at full load and full voltage simultaneously generators larger than 2,000 kilowatts. Rather do they elect to provide these two conditions separately, and accomplish virtually the same result, using only 5 per cent of the power that would be required in the former case. Similarly with the New Haven, it would have been quite impossible to have duplicated the operating conditions in the case of the generators or circuit-breakers. A temporary duplicate test system was impossible. The test would have been made on the original apparatus had it been possible, but time was not available, as has been pointed out in the paper under " electric passenger service ", in which an attempt was made to describe the pressing force that was constantly brought to bear on the New Haven engineers to begin electric service.

It is a pleasure, however, to read Mr. Stillwell's commentary that the four month's record of operation, as presented in the paper, was not a discouraging one, in the realization that the average for the train-minute delays during the last five months are 13½ per cent of the average of the four months cited in the log.

In response to Mr. Behrend's question in regard to the use of a 2-phase rather than a 3-phase generating plant, as applied to the New Haven conditions, I think this is a point deserving of a very careful explanation. Power house location has much to do with the choice between these two systems. In the case of a 2-phase system, it is natural to suppose, in order to secure the highest copper efficiency, that the point of divergence of the two phases should take place at the power house, if the power house is on the line of the railroad. Examining the location of the power house in the case of the New Haven, it is to be noted that about 18 miles of track lie west of the station, while about 3½ miles lie east of it. Thus it is quite clear that had the station been designed for two phases, they would have been very much unbalanced, especially as the train density is heavier per mile of track on the longer section, which, of course, would be a very unfortunate distribution of load in the windings of the generator.

In the operation of polyphase motors for shops and for street-railway-station drive along the line of the railroad, it would be necessary to intermingle the two phases of the system using the track for a common return of the currents of the two phases in quadrature. This would not introduce any features that are distinctly inferior to the present arrangement of the three phases throughout the length of the system. The question of voltage regulation for a 2-phase distribution, however, offers a decidedly serious aspect, as it is quite clear that it would be impossible to keep the voltages of both phases constant, unless the load on each was always the same. In the case of the 3-phase, we regulate the voltage of the propulsion phase, and the copper-clad rotors of the generators smooth out to a great degree the unbalanced voltages on the two other phases. I believe the deciding points against the 2-phase propulsion are the difficulties incident to loading the phases equally and maintaining voltage regulation.

The relative temperatures due to operation on alternating and direct-current, to which Mr. Behrend refers, I regret have not been obtained. The conditions of operation on the alternating-current zone and direct-current zone are so absolutely different that a comparative set of figures would be impossible, unless they were obtained under the auspices of test conditions. Later, this information may be obtained and will be gladly offered.

I note by Mr. H. F. Parshall's contribution that in 1901 he was appointed by the Board of Trade a member of the tribunal, presided over by the Hon. Alfred Littleton, to determine whether or not such an alternating-current system, as proposed by Ganz, was suitable for the underground railways of London. Immediately follows his conclusions that the alternating-current system was unfit for application upon the aforesaid railways, even though this date was previous to Mr. Lamme's paper on the Washington, Baltimore and Annapolis single-phase railway read before the American Institute of Electrical Engineers, at New York December 26, 1902,* which might have been said to be the entering wedge of the single-phase motor in its application to the propulsion of trains. Engineers of this country would surely look for a few grey hairs on motors of any design existing over a period of eight years, and so I do not wish to be counted out in the first ranks to congratulate Mr. Parshall in this eminent decision, which sounded the death-knell to the alternating-current motor for the subways of New York and the underground railways of the City of London. The London and New York subways offer about as much comparison to the New York, New Haven and Hartford Railroad Company's conditions as a steamboat does to a flying machine, and so I must leave this subject abruptly, and pass to a few concrete statements, which Mr. Parshall has made, and which seem to have been arrived at by projected hypothetical curves. A few brief counter statements may save time. The perfected alternating-current motor does not weigh 40 per cent more than a direct-current motor of the same capacity. If the air-gap of the alternating-current motor is of a character which permits the revolution of the armature in its bearings, and requires no greater maintenance than the direct-current motor, it does not matter how much smaller it is than the direct-current motor air-gap. Higher armature speeds are a specific advantage rather than disadvantage, in view of this characteristic having excellent application to the direct-connected type of locomotive. Our experience, though possibly not as great as Mr. Parshall's, does not prove that the cost of the high-tension overhead system properly installed is greatly in excess of a third-rail system. It is possible that the overhead wires and bridges necessary to carry them may cost more than the third rail, though even these may be equated. I can even conceive of the overhead contact construction on an alternating-current system being more expensive, *per se*, in first cost, and yet more economical in use, thus again we have this unfortunate feature presented of only looking at a part of a system instead of its whole.

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* Transactions, vol. xx, p. 15.

The alternating-current commutator is in itself heavier than the direct current, but practice and experience in this case has not substantiated Mr. Parshall's theory that the maintenance " ..... is nearly double that of a direct-current equipment of like capacity ". A few facts scattered in this nest of hypothetical reasoning may be useful, one among the number being that our present operating sheets show that our operating costs, *per se*, on the direct-current zone are just 40 per cent greater than that of the alternating current. At the time of presenting the paper on the " Log of the New Haven Electrification " it had been in commercial operation just four months, and I cannot refrain from quoting the last few lines of Mr. Parshall's discussion: " Concerning all that has gone on in the New Haven system up to September 5, 1908, which appears to be the termination of Mr. Murray's log, there is absolutely nothing to indicate that during 1909 some such series of occurrences are not again to be expected. All that has occurred may be expected to occur again in some form or another, since electric traction apparatus does not manifest all its faults during the first few months of operation ". Is not the first commentary upon this closing, encouraging eulogy a disappointment, that one is willing to make up his mind to condemn a system four months after its birth? Is this not a brief period during which to compose its obituary? Secondly, I can only say that " All that has occurred " *has not* " occurred again ", and whether it will in " some form or another " is so closely related to indefiniteness that analysis itself is duped, and prophesy becomes a helpless paralytic.

Mr. Armstrong opens his discussion with the following startling sentence, which contradicts everything that follows. " The enthusiastic coöperation of the engineers of the railroad company and the manufacturing company has brought this alternating-current operation to its present success and nothing but admiration can be expressed for the courage and ingenuity shown in overcoming the difficulties met with in operation ".

In thanking Mr. Armstrong for thus felicitating us, I am sure I will be pardoned for the number of exceptions that I must take to his subsequent remarks, in view of their almost complete inconsistency with the facts.

1. The New Haven specifications, as doubtless looked over by Mr. Armstrong, were drafted to make them inclusive of the operation of electric locomotives from New York to New Haven. The installation, therefore, of the alternating-current system of propulsion was not to *demonstrate* the suitability of that system to possible future extension of the road. It so happens that it has accomplished this purpose, but this is off the point, and the interesting feature of Mr. Armstrong's statement in the second paragraph of his discussion, is his full commitment to the 600-volt, or the 1200-volt, direct-current system, as the system applicable to the New Haven conditions, inclusive of the zone above described.

It is interesting to note the seeming pleasure in which Mr. Armstrong points to the "material changes" that were made to the locomotives and the generating and distributing systems. Following upon this is his statement of Mr. Wilgus's report of the cost at $55,000 a mile of our overhead construction. Why bring in Mr. Wilgus? Mr. Wilgus had nothing to do with either the estimates or the checking of them in actual practice. It is difficult to conjecture how he even arrives at these figures. Also how is this relevant to the paper? It does not discuss costs.

2. This inconsistency comes to mind in viewing Mr. Armstrong's guesses on the weights of the locomotives. These are completely without foundation.

3. Mr. Armstrong refers to published figures on the trolley construction, which as a matter of fact have never been published, not to mention inconsistency No. 4, in which we find Mr. Armstrong increasing the weight of the locomotives 50 per cent, for which he has absolutely no basis, and in which statement he is again absolutely wrong. Mr. Armstrong advises that the present weight of our locomotive approaches fairly close to the weight of the locomotive which he estimated would be required to perform the service originally specified. Doubtless Mr. Armstrong's experience in the design of alternating-current locomotives would have permitted us to make a closer approximation. It has never been my pleasure to have seen an alternating-current locomotive of Mr. Armstrong's design, though this does not preclude the possibility of one being on the rails. The only sure conviction I have, however, is that neither he nor his associates offered to design one which, with an amount of capacity equal to that of New Haven locomotive, was lighter.

I confess to a slight agreement with Mr. Armstrong's statement that the object of the New Haven electrification was of a far-reaching character—at least, far enough to reach to New Haven. How Mr. Armstrong can commit himself to such a statement that the New Haven trolley construction costs 80 per cent more than the 600-volt third rail, and that the locomotive costs double the amount of a locomotive sold another company, without even a film of foundation for his statements, is really remarkable. To deny them flatly is, I judge, sufficient.

Such remarks draw one almost to the necessity of discussing comparative figures of the one system with the other, as it is not to be denied either within or without the ranks of the two companies interested, that the New Haven road knows the investment costs and operating expenses of both systems. Some day the dictates of progress may demand an exposition of these facts, but they can not be drawn out by baseless innuendoes of the character above cited.

Mr. Armstrong's tables in reference to weights and horse powers of the New York Central and New Haven locomotives are wrong, in respect to the data he assigns to the New Haven columns. Again we have the brilliant reference to the 1-hour performance of the locomotives, completely ignoring the continuous capacity for which the New Haven locomotives were designed. This is not better exemplified than in the table that follows, showing the list of train weights above 400 tons which the New York Central locomotive has handled. The table would have been more useful to an engineer had an asterisk been attached with the notation that none of these trains were hauled to a distance greater than 12 miles.

To Mr. Armstrong's generous offer that I correct any error concerning the New York Central company's train-minute delays in view of my access to their official records, in the table which appears on the closing page of his discussion concerning the train-minute delays on the two systems for the months of July, August, September and October, 1908, I would say that were an error discernible, I would trust that it would prove the train-minute delays less than the number he has cited. I will refrain even from checking Mr. Armstrong's statement of train-minute delays he charges for the New Haven system over the same interval. My acquaintance with the officials of the New York Central company leads me to believe that they regret this form of argument which Mr. Armstrong advances, knowing that their system, incorporating the principles of 20 years' experience, and in operation one year previous to that of our own, should be compared with the first four months of a system whose lines were so radically different from their own, and whose principles were of such an entirely different character. It is interesting to note, however, that the average for the train-minute delays during the past five months following the four months cited in the paper are 13½ per cent of the average during the period of operation the paper includes.

Since Mr. Armstrong's desire to compare operating statistics has crystallized into the train-minute delay table which he has published, doubtless a reply more to the point of his argument would be the statement of the fact that notwithstanding the main line New Haven electrification is inclusive of both alternating- and direct-current operation, with an average of 135 trains a day, the actual number of train-minute delays during the whole period of operation since 100 per cent service has been under electrical control, has not been equal to the train-minute delays that are charged up against the two straight alternating-current cars operating upon the New Canaan branch during two of the four months cited in the paper. I feel justified in making reference to this fact, in order to substantiate Mr. Armstrong's opposition to the single-phase situation, for on this branch the equipments are of a design better known to himself, but I am happy to be able to record the fact that our position is fortunate in that should the New Canaan situation fall a victim to a policy which I understand is being advocated, we will not have to *go back* to the direct-current form of propulsion.

While the intent of the paper did not include a desire to compare the electrification of the New Haven with that of the New York Central, it seems that this phase of the situation developed in the discussion, and Mr. Storer has offered some very pertinent and interesting inquiries, the answers to which doubtless will come later. The most interesting part of his discussion to me is the emphasis he lays on the necessity of making system comparisons rather than the comparison of the individual parts of systems to each other.

It is very interesting to note Mr. Lyford's statistics in regard to wear on the contact wire and to note his prediction of a life of between 20 and 30 years. This corroborates micrometer measurements made on the steel wire during the past nine months of operation.

I have been very much interested in Mr. W. N. Smith's analysis of the situation, and I think he has placed his finger upon the keystone of the arch of successful alternating-current operation when it rests upon the overhead line. As stated in the paper, the three great links in the chain of electric propulsion are the power house, line and locomotives. As Mr. Smith has pointed out, power houses and locomotives may be relayed, but the line must stand alone, at least over a specified single piece of track. His analysis is to the point when he shows that the train-minute delays were the greatest in duration when occurring by reason of line failures. It was with this point in view that the author of the paper made the statement that, "In the month of May, 1908, it became evident to us that within at least one month from that date, if some change was not effected in the contact wire, the New Haven electric service would cease." But by far the most pleasing feature of Mr. Smith's contribution is that with finger pointing to the single link that had to be intact to ensure electric service, and while assigning it to its great degree of importance, his mind dwelt at the same time upon what the whole system stood for as a means to an end, and which must have been inclusive of safety, reliability of service and economy of operation.

Mr. Phillip Dawson's contribution to the discussion, in the form of the description of the London, Brighton and South Coast Railway Company, which uses the overhead single-phase system, is of much interest. It is to be noted that on this construction the spans are very much less than in the New Haven. To me the most interesting piece of metal in the overhead system is the contact wire, and I note that on the London, Brighton and South Coast Railway, the trolley wire is drawn up and anchored at both ends. It is quite possible that the clips Mr. Dawson has described as supporting the contact wire will be sufficiently light to prevent kinking at the hanger points. This arrangement will be greatly fortified if, as Mr. Dawson states, speeds of 45 miles an hour will not be exceeded. The double messenger triangular form of hanger offering a more rigid form of construction, and a greater degree of inertia at the hanger points, shortly proved itself undesirable for the speed conditions that exist upon our lines, and I feel quite sure that even in the form of single catenary suspension, our conditions would not permit the form of construction as adopted and described by Mr. Dawson. In short, our experience with the overhead construction leads me into the following brief specification for an overhead contact wire.

1. One single steel stranded messenger cable with deflection corresponding to economical values fixing distance of span.
2. One horizontal solid copper conductor supported from steel messenger at intervals of 10 ft. with light tension on same.
3. One horizontal solid grooved steel (contact) wire supported by light clips (weight not greater than 9 ounces) from the solid copper wire at mid-points between messenger hangers. The tension in this wire not to exceed the elastic limit of the steel at lowest temperature.

This auxiliary or contact wire as described under (3), it seems to me has as much right for existence as the floor of a highway bridge. To make contact on the copper wire would be the same as running on the members of a bridge, which, while consistent with the past practice of the electrical engineer does not match up with the precedent established long before the electrical engineer had to design his bridges for electrical traffic. The steel wire offers a cheaper and more easily replaced floor, and the conductor system always remains intact with undiminished efficiency.

The double-bow pantagraph collector with renewable contact strips has been tried out on the New Haven system. We did not get a very great deal of encouragement out of this form of collector; however, with the varying heights which highway bridges have dictated the contact wire to be, and with a continual deposit of steam locomotive discharges upon it, not to speak of the very high-speed conditions our collectors are subjected to, these may possibly have qualified the success which I only trust will accrue in their use on Mr. Dawson's road.

In answer to Mr. Ivan Ofverholm's inquiry in regard to the effect of smoke of the locomotives on the steel contact wire, I would say that our experience in connection with this deteriorating influence that the electrification has to contend with at present, is not so great as I had anticipated. A careful observation on the steel wire during the past nine months does not indicate that the blast from the locomotives has had much, if any, effect.

In connection with Mr. Ofverholm's statement concerning the doubling up of our messenger cable insulators, I see that he has referred to Fig. 13 descriptive of the yard construction. He is quite right that the insulators in this case were placed in parallel. On this occasion, however, this arrangement was made in order to resist mechanical rather than electrical strains. The strain in the cross catenary, which supports trolleys over 10 tracks, is 14,000 pounds. To-day porcelain insulators capable of resisting a mechanical strain of 40,000 lb. and 40,000 volts are at hand, but it was decided that single insulators of the character shown in the picture, which were the only ones then available, would not be sufficient, with proper margin of safety, to withstand this strain, and a special yoke was constructed upon which were installed the two insulators, to which Mr. Ofverholm has referred. A reference to Fig. 8, though not as clear as if the picture had been taken closer to the insulator, shows two insulators of the same type in series, this being the arrangement throughout the system over the main line tracks where they are subject to the blast of the steam locomotives.

Concerning Mr. Eveleth's suggestion that had we adopted the circuit-breakers of his design a large portion of the serious delays would have been obviated: even granting that his circuit-breaker would have operated in the exemplary manner described, I feel sure that the oversight in not having adopted it will be excused in our having considered it a part of the detail to be supplied by a company which believed *first* in the system, before they believed in the circuit-breaker. We may yet have an opportunity to use some of Mr. Eveleth's circuit-breakers though I doubt if the results can at present be bettered.

*A paper presented at a meeting of the Pittsburgh Section of the American Institute of Electrical Engineers, Pittsburgh, Pa., October 2, 1907.*

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# METHODS FOR LOCATING TRANSPOSITIONS OF WIRES AND SPLIT PAIRS IN TELEPHONE AND TELEGRAPH CABLES

BY HENRY W. FISHER

Some of the telegraph companies demand that there shall be no transpositions of wires in any of the layers in a telegraph cable. By this is meant that the wires of every layer must have the same relative order at each end of the cable. There is usually a tracer, or wire covered with different colored paper from the rest in every layer, and by counting from this tracer any particular wire can be located at any point in the cable. If a wire is fifth from the tracer in a clockwise direction at one end of the cable, it will be fifth from the tracer in a counter clockwise direction at the other end of the cable. By this general plan it becomes possible to identify wires without resorting to some of the common methods of testing. However, in order to be able to place implicit reliance in a scheme of identification of this sort, not only must the cables be manufactured correctly but the jointing must be made by skilled men who are careful to connect the wires of each layer in consecutive order, and as an extra precaution make repeated tests at both ends of the jointed sections as the work of splicing progresses. Even after exercising the greatest care, a transposition may occur. The object of the present article is to show how a fault of this kind can readily be located by some methods devised by the author.

To do this, a ballistic galvanometer, battery, condenser, and discharge key can be employed, but the writer prefers to use an alternating current or continually reversed direct current, a wheatstone bridge or its equivalent, a condenser, and, as a current detector, a telephone, or, still better, a vibration galvanometer.

Instruments are now made which are suitable for this work, provided that the length of cable is great enough to obtain sufficiently discriminating values between the various tests made.

As the methods employed deal entirely with measurements of electrostatic capacity, which are ably described in many text and hand-books, the writer will here only briefly show by diagram and description, the arrangement of sensitive apparatus which was employed to verify the accuracy of the methods used.

Fig. 1 gives in diagrammatic form the connections and apparatus employed. $R$, $R'$ and $R''$ are non-inductive resistances wound also so as to have a minimum capacity. $G$ is the vibration galvanometer, $C$ a standard condenser, and $A$ $C$ the alternating-current source which, by means of an electrically driven tuning-fork arrangement, was kept at a frequency that gave maximum vibration to the galvanometer needle. The resistance $R''$ is needed to obtain the condition of balance or zero vibration of the galvanometer.

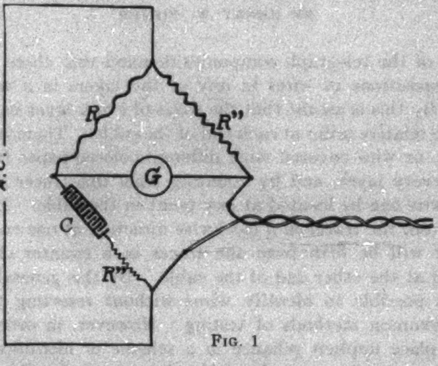

FIG. 1

The plan of operation was to keep $R'$ constant and vary $R$ and $R''$ until the galvanometer ceased to vibrate. $R''$ does not enter into the calculation of capacity which is represented by the formula $\frac{R}{R'}$ $C$. Therefore, as $R'$ and $C$ were constant, the relative capacities are proportioned to $R$, and as we deal here entirely with relative values, the figures given for the different tests are the $R$ resistances required to give zero vibration to the galvanometer.

*Telegraph cables.* Before proceeding to the derivation of formulas, it is important to remember that the theory of relative capacities with different connections in bunched or paired telegraph or telephone cables is extremely complex. The formulas here given are not absolutely correct, on account of certain very small capacity effects that are ignored for the sake of simplicity. They are probably close enough, however, because it is impossible to make cables of this sort, and not have in the capacities of different wires, variations of as much as five or ten per cent., which would be sufficient to cause great discrepancies, even if theoretically correct formulas were employed.

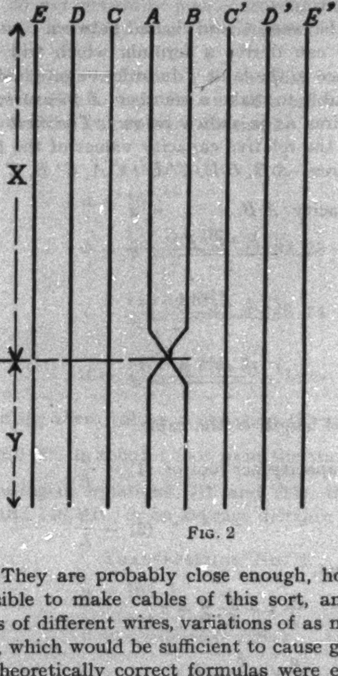

FIG. 2

We shall first consider the simplest case; namely, that where adjacent wires in a telegraph cable are transposed, and after that we shall give general directions which are applicable to almost any condition of single transposition.

Fig. 2 represents a number of wires in a layer of cable. *A* and $B$ are the two wires which are transposed at a distance of $X$ feet from the end where the test is applied and $Y$ feet from the other end of the cable. In representing a test between two wires the letters designating each will be coupled together thus: The capacity between $A$ and $B$ will be spoken of as capacity $A\,B$.

The general plan of procedure is to determine the capacity between adjacent wires and also the capacity between wires $C$ and $E$, the latter being selected so that the number of wires between $C$ and $E$ is equal to the number between $C$ and $B$ or between $C'$ and $A$.

If the capacities between $C$ and $A$, and between $C$ and $B$, are then measured we can derive a formula which will give the approximate distance to the fault. In order to get good average results, it is advisable to make a number of measurements of similarly placed wires as is shown below. The first thing to do is to determine the relative capacity values of the following combinations of wires—$A\,B$, $C\,E$, $C'\,E'$, $C\,A$, $C'\,B$, $C\,B$, $C'\,A$.

$$\text{Let capacity } A\,B = a \tag{1}$$

$$\text{“ \quad “ } \frac{C\,E + C'\,E'}{2} = b \tag{2}$$

$$\text{“ \quad “ } \frac{C\,A + C'\,B}{2} = c \tag{3}$$

$$\text{“ \quad “ } \frac{C\,B + C'\,A}{2} = d \tag{4}$$

Let $L$ = the total length of the cable.

$$\text{The capacity per foot of (1)} = \frac{a}{L} \tag{5}$$

$$\text{“ \quad “ \quad “ \quad “ \quad “ (2)} = \frac{b}{L} \tag{6}$$

From which we get,

$$\frac{a}{L}x + \frac{b}{L}y = c \tag{7}$$

$$\frac{a}{L}y + \frac{b}{L}x = d \tag{8}$$

Solving equations (7) and (8) for $x$ we have,

$$x = \text{the distance to the fault} = \frac{a\,c - b\,d}{(a-b)\;(a+b)} \times L \tag{9}$$

Now as $x+y = L$, we can substitute $y = L-x$ in equations (7) and (8) and get the following results,—

$$x = \frac{c-b}{a-b} \times L \qquad (10) \quad \text{from equation (7)}$$

$$x = \frac{a-d}{a-b} \times L \qquad (11) \quad \text{from equation (8)}$$

Equation (9) is the proper one to use because equations (10) and (11) do not generally give concordant distances, although their average is usually near the distance obtained by equation (9).

To give the above formulas a practical test, two wires were transposed at 130 ft. from the end of a cable measuring 280 ft. and the following values were obtained.

TRANSPOSITION No. 1.

$$a = 167$$

$$b = \frac{132.5+133}{2} = 132.75$$

$$c = \frac{148+145.5}{2} = 146.75$$

$$d = \frac{147.5+150.5}{2} = 149$$

Substituting these values in equation (9) we get,

$x = 128.9$ ft., or about 1 foot from the transposition.

Substituting in equations (10) and (11), the values of $x$ are 113.6 ft. and 146.1 ft., or an average distance of 129.8 ft.

TRANSPOSITION No. 2.

$$a = 161.5$$

$$b = \frac{127+130}{2} = 128.5$$

$$c = \frac{138.5+141.5}{2} = 140$$

$$d = \frac{140.5+142.5}{2} = 141.5$$

Substituting these values in equation (9) we get,

$x = 129.6$ ft., or about 0.5 ft. from the transposition.

Substituting in equations (10) and (11) the values of $x$ are 96.9 ft. and 168.4 ft., or an average distance of 132.6 ft.

As mentioned before, it will be noted here that the values found by equations (10) and (11) differ widely. This may be partly due to inequalities in manufacture, but is more likely caused by the formulas being only approximate. The average value of ($a$) as measured should be slightly too high, and this would make the results by formula (11) too great. In formulas (10) and (11) nearly equal terms are subtracted and this is always a source of error. This kind of test is necessarily of such nature that even slight irregularities in manufacture may cause great differences in the calculated distances. It is for this reason that so many measurements have to be taken, for we are enabled thereby to obtain average results.

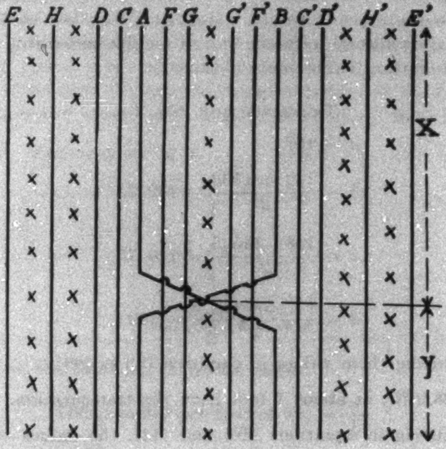

Fig. 3

We will next consider the case where there are several wires between the transposed wires, which, as before, should be marked $A$ and $B$. The wire adjacent to $B$ should be marked $C'$ and that next to $A$ should be marked $C$, as indicated in Fig. 3.

Then select and mark a wire $E$ such that the number of wires between $C$ and $B$ is equal to that between $C$ and $E$. Also select and mark a wire $E'$ such that the number of wires between $C'$ and $A$ is equal to that between $C'$ and $E'$.

The tests can now be made exactly as described above, with the exception that for capacity $A\,B = a$, the capacity between several pairs of adjacent wires near but not including $A$ or $B$ should be determined, and the average of these taken as ($a$) in formula (9). The wires generally measured are $C\,D$, $F\,G$, $F'\,G'$, $C'\,D'$. After the values of ($b$), ($c$), and ($d$) are found, the distance to the fault can be calculated by equation (9), and, if desired for the sake of comparison, by equations (10) and (11).

A separate set of values for $b$, $c$, and $d$ can be found by selecting the wire $H$, so that the number of wires between $F$ and $H$ equals the number between $F$ and $B$; also the wire $H'$, so that the number of wires between $F'$ and $H'$ equals the number between $F'$ and $A$.

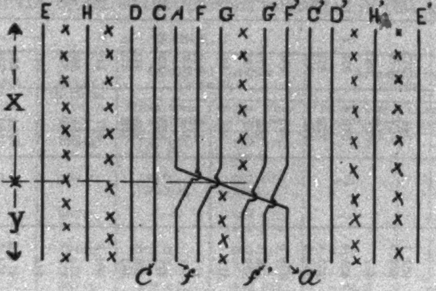

FIG. 4

Then

$$b = \frac{F\,H + F'\,H'}{2} \quad c = \frac{F\,A' + F'\,B}{2} \quad \text{and } d = \frac{F\,B + F'\,A}{2}$$

With these and the previously determined value of ($a$) a check value of $x$ can be found by equation (9).

Fig. 4 illustrates the case of a single displaced wire $A$. Here the number of wires between $C$ and $E$ and between $C'$ and $E'$ equals the number between $C$ and $a$. Also the number of wires between $F$ and $H$ and between $F'$ and $H'$ equals the numbe

TABLE I.

RELATIVE CAPACITIES = *R* IN FIG. 1.

| Test between wires | Fault No. 1 | | Fault No. 2 | | Fault No. 3 | | Fault No. 4 | | Fault No. 5 | | Fault No. 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *m* | *n* | *m* | *n* | *m* | *n* | *m* | *n* | *m* | *n* | *m* | *n* |
| *C D* | 412 | 416.5 | 421 | 426.7 | | 384 | 375 | 383 | 356 | 363 | 355.5 | 362.5 |
| *F G* | 419 | 427.5 | 419 | 422.5 | | 380 | 379 | 383 | 368.5 | 376 | 367.5 | 375.5 |
| *F' G'* | 410 | 419 | | | | 373.5 | | | 377 | 386 | 375.5 | 385.5 |
| *C' D'* | 403 | 412.5 | 420 | 427 | | 381 | 382 | 385 | 376 | 378 | 372.5 | 377.5 |
| Average = *a* | 411.3 | 419 | 420 | 425.4 | | 379.6 | 378.7 | 383.7 | 369.4 | 375.8 | 367.8 | 375.4 |
| *C E* | 344.5 | 358.5 | 343 | 357.5 | | 324 | 313 | 324.5 | 304 | 313.5 | | |
| *C' E'* | 342 | 359 | 344 | 359.5 | | 328 | 307 | 320.5 | 301 | 314 | | |
| Average = *b* | 343.2 | 358.8 | 343.5 | 358.5 | | 326 | 310 | 322.5 | 302.5 | 313.8 | | |
| *C A* | 357 | 373 | 354.5 | 369 | | 360 | 371 | 380.5 | | | | |
| *C' B* | 353.5 | 369.5 | 362.5 | 377 | | 357.5 | 365 | 377.5 | | | | |
| Average = *c* | 355.2 | 371.2 | 358.5 | 373 | | 358.8 | 368 | 379 | 319.5 | 329.5 | | |
| *C B* | 405 | 413.5 | 402 | 411 | | 353 | 327.5 | 345.5 | | | | |
| *C' A* | 398 | 407.3 | 401.5 | 411 | | 353 | 325.5 | 341.5 | | | | |
| Average = *d* | 401.5 | 410.8 | 401.8 | 411 | | 353 | 326.5 | 343.5 | 361 | 369.5 | | |
| *F H* | 348.5 | 361.5 | 354 | 363.5 | | 325 | 318 | 328 | | | 297.5 | 313.0 |
| *F' H* | 335.5 | 352.5 | 354 | 365 | | 330 | 316.5 | 327.5 | | | 302.5 | 315.5 |
| Average = *b* | 342 | 357 | 354 | 364.3 | | 327.5 | 317.3 | 327.8 | | | 300 | 314.3 |
| *F A* | 370 | 376 | 369 | 375 | | 363 | 368 | 374.5 | | | | |
| *F' B* | 356 | 369 | 366 | 373 | | 355 | 373 | 380 | | | | |
| Average = *c* | 363 | 372.5 | 367.5 | 374 | | 359 | 370.5 | 377.3 | | | 323.5 | 337 |
| *F B* | 408.5 | 417.5 | 407.5 | 414.5 | | 354.5 | 334 | 340.5 | | | | |
| *F' A* | 399 | 406.5 | 398 | 404.5 | | 350 | 338.5 | 347 | | | | |
| Average = *d* | 403.7 | 412 | 402.8 | 409.5 | | 352.3 | 336.3 | 343.8 | | | 365.5 | 374 |

*m* indicates that other wires in cable were free and not grounded.
*n* indicates that other wires in cable were all grounded.

between *f* and *a*. Having tagged the wires as just described, and as illustrated in Fig. 4, the same connections and tests as mentioned above can be made except those involving the wire *B* which does not exist here. Therefore only one-half the number of tests can be made to get *c* and *d*, and hence an accurate location of the fault cannot be expected.

Tables 1 and 2 give the results of tests on telegraph cables.

Fault 1 had 3 wires between *A* and *B*.
" 2 " 2 " " "
" 3 " 3 " " "
" 4 " 2 " " "

Fault 5 was a single displaced wire as illustrated in Fig. 4 and there were 4 wires between *a* and *c*. All the figures obtained are given in the tables, so that persons interested in this subject can study them, noting the change of capacity for different connections.

TABLE II

| No. of Fault | Length of cable | Actual distance to fault | Calculated distance to fault | | Average error in feet | |
|---|---|---|---|---|---|---|
| | | | Other wires not grounded | Other wires grounded | Other wires not grounded | Other wires grounded |
| No. 1 | 1098 ft. | 208 ft. | 176.1 ft.<br>234.5 ft. | 189.9 ft.<br>205 ft. | — 2.7 | —10.5 |
| No. 2 | 1098 ft. | 208 ft. | 238 ft.<br>252.5 ft. | 237.6 ft.<br>226 ft. | +37. | +24. |
| No. 3 | 1021 ft. | 557 ft. | —— | 569.8 ft.<br>581.5 ft. | —— | +18.6 |
| No. 4 | 1021 ft. | 794 ft. | 823 ft.<br>803 ft. | 818 ft.<br>819 ft. | +19. | +24.5 |
| No. 5 | 987 ft. | 265 ft. | 193.6 ft.<br>203.8 ft. | 209.6 ft.<br>181.9 ft. | —66.3 | —69.2 |

Table II gives the errors in feet; they are sometimes + errors and sometimes − errors, thus tending to show that inequalities in manufacture are probably largely the cause of the discrepancies.

*Telephone cables.* Telephone cables are made up of twisted pairs, and when they are jointed no attempt is made to connect the pairs in any definite order. In fact most of the telephone companies mix the pairs of the different layers up as much as possible, thereby making the capacity of the pairs more uniform and the cable more efficient for telephone service. On account of this method of installation, it is more difficult to locate split pair faults accurately.

Fig. 5 illustrates what is meant by a split pair. The wires *C* and $F$ are connected straight through the cable, but $D$ and $E$ are cross-connected. If those two pairs are used for telephone service there will be more or less cross-talk, depending upon the location of the transposition. Hence the need of locating the joint where the wrong connection has been made and rectifying the mistake. Some of the methods which have been used for locating split pairs are not reliable, giving only a rough approximation.

After a consideration of the former work presented in this paper, it will be seen that the same general methods may be employed provided we can make the capacity $b$ fairly uniform throughout the cable, and then either measure it directly, or else eliminate it from equation (9). The first can be accomplished fairly well by grounding all the wires in the cable except those used in the test, and $b$ can be eliminated from equation (9) as will now be shown.

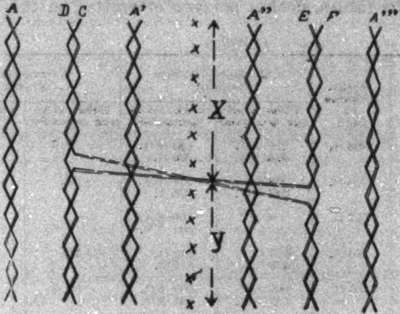

Fig. 5

Referring to Fig. 5, $A$, $A'$, $A''$, and $A'''$ represent four good pairs. $C$, $D$, $E$, and $F$ represent the split pairs, $C$ and $F$ being connected correctly, $D$ and $E$ being cross-connected. The capacity between the wires of the individual pairs $A$, $A'$, $A''$, and $A'''$ should first be measured and the average taken as the value of $a$. It is not absolutely necessary to take just four pairs, but enough should be measured to insure a good average result.

As in the case of telegraph cables, we will let the capacity

$$\frac{CD + EF}{2} = c \text{ and } \frac{CE + FD}{2} = d.$$

Now by referring to Fig. 5 we can say that the capacity $b$ is equal to the capacity $C\,E$ throughout the distance $x$ added to the capacity $C\,D$ throughout the distance $y$. Now as $a$ is the capacity of a pair, we can say that $a$ equals the capacity $C\,D$ throughout the distance $x$ added to the capacity $C\,E$ throughout the distance $y$. This gives the relation $b = c+d-a$. Substituting this value of $b$ in equation (9) we get

TABLE III

RELATIVE CAPACITIES = $R$ IN FIG. 1.

| Test between wires | Fault No. 1 | Fault No. 2 | Fault No. 3 | Fault No. 4 | Fault No. 5 | | Fault No 6 | |
|---|---|---|---|---|---|---|---|---|
| | $m$ | $m$ | $m$ | $m$ | $m$ | $n$ | $m$ | $n$ |
| $A$ | 555 | 523 | 527 | 554 | 827 | 827 | 827.5 | 826.5 |
| $A'$ | 537 | 530.5 | 540 | 576 | 832.5 | 833 | 839 | 838 |
| $A''$ | 538 | 519.0 | 618 | 589 | 837 | 838.5 | 848.5 | 846 |
| $A'''$ | 536 | 547.5 | 592 | 566 | 830 | 830 | 831.0 | 829.5 |
| Average $a$ | 541.5 | 530 | 569 | 571.2 | 831.6 | 832.1 | 836.5 | 835 |
| $C\,D$ | 505 | 472 | 466 | 478 | 681 | 710 | 762.5 | 770 |
| $E\,F$ | 468 | 485 | 504 | 498 | 686.5 | 716 | 766 | 773.5 |
| Average $c$ | 486.5 | 478.5 | 485 | 488 | 683.7 | 713 | 764.3 | 771.8 |
| $C\,E$ | 497 | 469 | 469 | 479 | 756.5 | 764.5 | 679.5 | 714.5 |
| $E\,D$ | 466 | 480.5 | 490 | 492 | 747.5 | 756.5 | 674.5 | 707.5 |
| Average $d$ | 481.5 | 474.8 | 479.5 | 485.5 | 752 | 760.5 | 677 | 711 |

TABLE IV

| No. of fault | Length of cable | Actual distance to fault | Calculated distance to fault | | Average error in feet | |
|---|---|---|---|---|---|---|
| | | | Other wires not grounded | Other wires grounded | Other wires not grounded | Other wires grounded |
| No. 1 | 586 ft. | 293 ft. | 305.6 | —— | +12.6 ft. | —— |
| No. 2 | 586 ft. | 293 ft. | 303.1 | —— | +10.1 ft. | —— |
| No. 3 | 586 ft. | 293 ft. | 302.3 | —— | + 9.3 ft. | —— |
| No. 4 | 586 ft. | 293 ft. | 297.3 | —— | + 4.3 ft. | —— |
| No. 5 | 1155 ft. | 433 ft. | 404 | 433.7 | —29. ft. | 0.7 ft. |
| No. 6 | 1155 ft. | 759 ft. | 797 | 765 | +38. ft. | 6.0 ft. |

$$x = \frac{(a-d)\ L}{2a-(c+d)} \tag{12}$$

Which is the formula to use for a split pair in a telephone cable?

Referring now to Tables III and IV, faults No. 1, No. 2, No. 3, No. 4 were purposely made in 585 ft. of 203 pairs No. 19 cable.

There were two, three, four, and five pairs respectively between the faulty pairs of each fault. It is evident that the farther the faulty pairs are apart, the nearer correct is the fault location. Tests were not made in this case with all the wires except the test wires connected to the lead cover, or else a less error in feet would probably have been obtained. Faults 5 and 6 were in the No. 13 pairs of a combination cable consisting of 15 pairs No. 19, and 10 pairs No. 13.

It is a notable fact that the error in feet is much smaller when all the wires not used in each test were connected to the lead cover, than when all wires were free.

Some tests were made using a ballistic galvanometer and the discharge deflection method, and good results were obtained. This method would probably be used the most in practice, but there are testing sets where the resistance method and a telephone are used; these are especially suitable for locating faults of the kind herein treated. One of these designed by the writer is giving good satisfaction in commercial use.

*Conclusions*. Sufficient tests are not here given to enable anyone to tell how successfully such faults could be located in practice, but the writer is of the opinion that relatively better results might be obtained, because the general average of many sections of cable would tend towards capacity uniformity, especially in telephone cables. The tests on telephone cables here recorded average better than those on telegraph cables. The methods would probably have a wider range of usefulness in telephonic than in telegraphic engineering work.

# BY-LAWS
OF THE
# AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

[*Adopted by the Board of Directors April* 22, 1904, *Amended February* 24, 1905, *March* 24, 1905, *February* 23, 1906, *May* 19, 1908, *and November* 13, 1908.]

The Constitution as amended May 21, 1907, authorizes the adoption of By-laws as follows:

ART. VII, SEC. 40. *The Board of Directors shall prepare and adopt a series of By-laws which shall govern its procedure and that of the committees, under this Constitution. Such By-laws shall be adopted or may be amended by a concurring vote of not less than twelve* (12) *members of the Board of Directors; provided, that the text of a proposed By-law or amendment shall be furnished to each member of the Board of Directors at least ten days before the meeting, at which a vote on the same will be taken.*

## BY-LAWS.
### MEMBERSHIP.

SEC. 1. Members, Associates, and Honorary Members, are authorized to use the following abbreviations indicating their grade of membership in the INSTITUTE.

| | |
|---|---|
| Honorary, | Hon. Mem. A. I. E. E. |
| Member, | Mem. A. I. E. E. |
| Associate, | Assoc. A. I. E. E. |

The term member (when printed without a capital), where used herein, includes Members, Associates, and Honorary Members.

It shall be the duty of all members to call the attention of the Secretary to the improper use of INSTITUTE badges or symbols, or to claims made by non-members that they belong to the INSTITUTE. The Secretary shall thereupon investigate the facts and lay the matter before the Board of Directors.

SEC. 2. An applicant for admission as an Associate who is not personally known to three members of the INSTITUTE, may refer for one or more of his three references preferably to a member or members of any grade in the societies designated in Section 3, or to any citizens of standing in the community; and the members of the Board of Examiners may then, if satisfied of his merits, endorse his application in the usual manner.

SEC. 3. An applicant for transfer who certifies that he is not personally known to five Members may refer for one or more of his five references to an Associate or Associates of the A.I.E.E., or to one or more professional engineers of recognized standing who may belong to any of the following named societies: American Society of Civil Engineers; American Society of Mechanical Engineers; American Institute of Mining Engineers; The Canadian Society of Civil Engineers; The Society of Naval Architects and Marine Engineers, all of America; or, the Institution of Civil Engineers, the Institution of Mechanical Engineers, or the Institution of Electrical Engineers, of Great Britain; or of any approved American or foreign national engineering body.

SEC. 4. The names of applicants for transfer to the grade of Member, after being recommended for transfer by the Board of Examiners, shall be posted in the PROCEEDINGS, and final action thereon shall not be taken by the Board of Directors until one month after such posting, in the case of all applicants residing in North America, and until three months after such posting, in the case of all other applicants.

SEC. 5. Objection to the admission of any candidate for the grade of Associate, or for transfer to the grade of Member, must be accompanied by reasons for such objection, all statements to be treated as confidential.

SEC. 6. The privileges attaching to membership in the INSTITUTE, shall not be accorded to applicants for admission until they have been duly elected, and have paid their entrance fees and current dues.

SEC. 7. A prompt notification of his election as an Associate, accompanied by a statement of his initiation fee and dues, shall be mailed to each candidate by the Secretary. A second notice of his indebtedness shall be sent by registered mail 30 days (60 days in the case of members residing outside of North America) later to every candidate remaining in arrears. The Secretary may, at his discretion, cancel the election of any applicant remaining in arrears 30 days (60 days in the case of members residing outside of North America) after the mailing of the second notice.

SEC. 8. A member who has resigned in good standing, may, on the approval of the Board of Directors, be reinstated without payment of entrance fee, and shall be entitled to admission to the grade last held by him, after review of his professional record by the Board of Examiners. If the applicant so elects, he may retain his original date of election or transfer, by payment of all dues which would have accrued during the interim, and he will then be entitled to such INSTITUTE publications issued during such period, as are available.

SEC. 9. Any resignations received by the Secretary not later than June 1st of any year (September 1st in the case of members residing outside of North America), may, at his discretion, be considered as having been received as of May 1st preceding.

SEC. 10. The rights and privileges of each Honorary Member, Member, or Associate, shall be personal to himself, and shall not be transferable or transmissible by his own act or by operation of law.

SEC. 11. An Honorary Member, Member, or Associate, whose membership shall terminate for any cause shall have no right or interest in any property of the INSTITUTE or any claim or privilege in or against the INSTITUTE or pertaining thereto.

### PAYMENT OF DUES.

SEC. 12. Annual dues are payable in advance upon receipt of bills dated May 1st, the beginning of each fiscal year.

SEC. 13. A bill for annual dues shall be mailed to each member on or about May 1st. On October 1st a second notice shall be sent to those in arrears. On March 1st following a third notice shall be sent by registered mail to those remaining in arrears, a copy of this section of the By-laws to accompany such notice. Any member remaining in arrears May 1st shall be placed on the Suspended List, shall receive no further INSTITUTE publications, and shall be debarred from enjoying its other privileges until reinstated. At its May meeting the Secretary shall submit to the Board of Directors a list of the delinquents, for its action thereon.

SEC. 14. The mailing of such bills or statements to the last address upon the office Mailing List, shall be considered a valid notice of indebtedness.

### BOARD OF DIRECTORS.

SEC. 15. The regular monthly meeting of the Board of Directors shall be held on the same day as the regular monthly meeting of the INSTITUTE. The meeting may also be held in any month when no regular INSTITUTE meeting occurs, the date of such meeting and the hour of all meetings to be set by the President.

### ELECTIONS.

SEC. 16. A Manager elected to fill a vacancy for an unexpired term shall be selected from those whose names appeared on the General Proposal List prepared for the last annual election.

SEC. 17. In preparing the Directors' Ticket, candidates shall be voted for by written or printed ballot. The names of candidates for Vice-president should be selected, as far as practicable, from different sections of the country.

SEC. 18. For the guidance of members in the selection of nominees for the annual election, there shall be published in the January and February PROCEEDINGS, each year; a summary of the nomination votes of the preceding year, containing the names of all persons having received at least three per cent. of the entire number of nomination votes cast, and also the names of all directors not included in this list and of ex-Vice-presidents and Managers who have held office at any time during the preceding five years.

SEC. 19. Nomination forms, as provided in the Constitution, shall be sent, upon application, to Associates who have qualified between the dates of February 1st and March 1st; and single copies only, of such nomination forms, shall be sent, upon request, as duplicates, to members who may have mislaid or destroyed their original copies. Nominations may, however, be written on blank paper if the regular form is not available.

### OFFICE ORGANIZATION.

SEC. 20. The office organization shall include an Assistant Secretary and an Editor.

The Assistant Secretary shall assist the Secretary, and, in his absence, may act for him, and shall have such other duties as may be specifically assigned to him by the Board of Directors from time to time.

The Editor shall report directly to the Secretary, and shall, under the direction of the Meetings and Papers and the Editing Committees, have charge of the publication of the PROCEEDINGS and of the TRANSACTIONS.

### JOHN FRITZ MEDAL.

SEC. 21. The representatives of the INSTITUTE on the Board of Award of the John Fritz Medal, shall be the President of the INSTITUTE, and his three immediate predecessors in office. Each year the president-elect, after assuming the active duties of his office, shall, on the third Friday in January, become a representative of the INSTITUTE on the Board of Award of the John Fritz Medal, and the functions of the senior past-president, in connection with this award, shall then cease and determine. In the event of the death or permanent disability of any of the representatives of the INSTITUTE on the Board of Award of the John Fritz Medal, the Board of Directors shall be empowered to select his successor from among the surviving past-presidents of the INSTITUTE, and such successor shall hold office for the term of the representative in whose place he is appointed.

### ADDITIONAL DUTIES OF COMMITTEES.

SEC. 22. Each standing committee shall have a regular monthly day of meeting, as far as practicable. All resolutions or reports which each committee shall forward to the Board of Directors for action, must be signed by the chairman.

SEC. 23. In addition to the duties prescribed by the Constitution, it shall be the duty of the Finance Committee to cause to be prepared for the information of the Board of Directors, a balance sheet each year, to September 30th, showing the financial condition of the INSTITUTE, including the state of each fund which may be separately invested; also to submit to the Board of Directors at its October meeting a budget of estimated receipts and expenditures for the ensuing year beginning October 1st. It shall also be the duty of the Finance Committee to have the bank books and securities of the INSTITUTE examined, prior to the annual financial statement made in the month of May, and to certify to their correctness.

SEC. 24. It shall be the duty of the Library Committee to advise in regard to the purchase of books or the acceptance of donations for library purposes, on behalf of the INSTITUTE; to prepare an annual report for the year ending April 30th, showing the state of the library, and giving the names of all donors to the library for the preceding year, which report, when accepted by the Board of Directors, shall be printed, and form part of the monthly PROCEEDINGS.

SEC. 25. The Meetings and Papers Committee shall accept no paper from a non-member unless directly authorized to do so by the Board of Directors.

SEC. 26. In addition to the duties prescribed by the Constitution, it shall be the duty of the Editing Committee to exercise a general supervision over all publications of the INSTITUTE. It shall also call the attention of the Meetings and Papers Committee to papers which it may deem unsuitable for publication in the PROCEEDINGS or TRANSACTIONS, assigning specific reasons therefor.

SEC. 27. Each temporary committee appointed to arrange for the holding of the Annual Convention, or for any other purpose involving expense to the INSTITUTE, shall prepare an estimate of its probable expenditure and submit it to the Board of Directors for approval.

SEC. 28. The functions and duties of temporary committees shall be defined by the Board of Directors. At the beginning of each administrative year the Secretary shall transmit to all the members of each temporary committee whose duties may be continued, copies of the original resolutions constituting such temporary committee. It shall be the duty of the Secretary to call the attention of the Board of Directors to work done by any temporary committee outside the scope of the resolution or resolutions which constituted it.

SEC. 29. The expenditures of the INSTITUTE shall be regulated by annual appropriations which shall begin on the first day of October of each year. Each committee shall submit to the Secretary for the information of the Finance Committee in preparing its annual October budget, an estimate of its requirements for the ensuing year.

SEC. 30. No standing or temporary committee shall, under any circumstances, exceed its authorized appropriation without first obtaining the sanction of the Board of Directors.

SEC. 31. For the information and guidance of these committees the Secretary shall each month send to the chairman of every committee which has incurred expense during the preceding month, the following information:

1. Total amount of all appropriations authorized for the current year by the Board of Directors for such committee.

2. Amount in dollars and per cent. of appropriation expended during the preceding month.

3. Amount in dollars and per cent. of appropriation expended during the current fiscal year, including the preceding month.

4. The same information for the corresponding periods of the preceding year, when available.

SEC. 32. The President may invite any non-member to discuss any paper presented at a meeting of the INSTITUTE, and the chairman of any Section may invite any non-member to discuss any paper presented at the Section of which he is chairman.

### PUBLICATIONS.

SEC. 33. The regular publications of the INSTITUTE shall include PROCEEDINGS, to be published monthly, and TRANSACTIONS, to be published quarterly, semi-annually, or annually.

SEC. 34. The PROCEEDINGS may have two principal divisions:

1. For current matter and INSTITUTE news;

2. For technical papers, discussions and other matter of an engineering character.

SEC. 35. The TRANSACTIONS shall contain such papers, discussions and other engineering matter previously printed in the PROCEEDINGS, as may be approved for publication in the TRANSACTIONS by the Meetings and Papers Committee and the Editing Committee.

SEC. 36. From the annual dues paid by each member, five dollars ($5.00) shall be deducted and applied as a subscription to the PROCEEDINGS for the year covered by such payment.

SEC. 37. The payment of the annual dues by any member shall entitle him to receive a bound copy of each volume of the TRANSACTIONS for the period covered by such payment.

SEC. 38. The paper or papers presented at the meeting in any month shall be published in the PROCEEDINGS, preferably in advance of the meeting.

SEC. 39. A paper, after being edited and revised for publication under the direction of the Meetings and Papers Committee, shall be returned to the author to obtain his consent to its publication as revised. In case the author shall not consent to publication in the form suggested by the said committee, and a revision acceptable to both the committee and the author cannot be arranged, the paper shall not be presented or published.

SEC. 40. A discussion or communication, after being edited and revised for publication under the direction of the Editing Committee, shall be returned to the author to obtain his consent to its publication as revised. In case the author shall not consent to publication in the form suggested by the said committee, and a revision acceptable to both the committee and the author cannot be arranged, the discussion or communication shall not be published.

SEC. 41. No paper, or written contribution to a discussion shall be given to the press for publication, in advance of its presentation, except by authority of the Board of Directors.

Sec. 42. No person shall receive monetary compensation from the reprinting of any paper or discussion presented before the Institute or before any Section or Branch without previous authorization from the Editing Committee.

Sec. 43. The Secretary is authorized to receive annual subscriptions for the monthly Proceedings, ending with the calender year, at the rate of $10.00 per annum for all countries to which the bulk rate of postage applies. To all other countries the price shall be $12.00 per annum, fifty per cent. discount to libraries.

Sec. 44. Existing bound volumes, or bound volumes hereafter published, may be sold to non-members at the following prices:

| | |
|---|---|
| Paper covers, Vols. I to IV, each | $2.00 |
| Paper covers, later volumes, per year | 10.00 |
| Cloth " " " " " | 11.50 |
| Half Morocco " " " " | 13.00 |

A discount of 10 per cent. from the above prices, either for volumes, subscriptions, or parts, may be allowed to publishers and dealers. Members and Associates shall be allowed a discount of 50 per cent. on parts or duplicate volumes to replace those lost or destroyed. They may purchase volumes issued prior to their election, when available, at $5.00 each, either in paper or cloth covers, or at $1.00 extra for half morocco binding.

Sec. 45. An Associate shall be entitled to receive the bound volume or volumes of the Transactions, beginning with the volume including the corresponding half year in which he has paid his entrance fee, and such single copies of the Proceedings for the same period as he may apply for, and which are available.

Sec. 46. A member who has presented a paper to the Institute, which has been printed in the Proceedings, shall be entitled, upon application, to 15 copies of the paper, or, at the Secretary's discretion, of the Proceedings containing such paper, and to the same number of copies of the discussion, provided such copies are available.

Sec. 47. A catalogue of members shall be published annually. A directory, in which the names are grouped geographically (Members' names shall be distinguished from those of Associates by a difference in type), may also be issued. The Constitution and By-laws of the Institute shall be printed in at least one of these publications. Either the catalogue or the directory, or both, at the Secretary's discretion, may be issued as a part of the Proceedings.

### Sections.

Sec. 48. The principal work of a Section shall be the holding of regular meetings for the presentation and discussion of papers on matters relating to electricity, and to the allied arts and sciences.

Sec. 49. A Section of the Institute may coöperate with other local engineering organizations in the holding of joint meetings, and may invite members of such organizations to its meetings.

SEC. 50. A petition for the formation of a Section shall specify the territory to be included and shall be signed by not less than 25 members residing therein.

SEC. 51. The territory of a Section shall include the locality naturally tributary thereto, but shall not include territory so remote that members cannot readily attend meetings.

SEC. 52. A Section shall be known as: The (name of place) Section of the American Institute of Electrical Engineers.

SEC. 53. In the initial Section organization only petitioners shall have the right to vote.

SEC. 54. In addition to INSTITUTE members the Section by-laws may admit other persons interested in engineering, who shall have all the Section privileges except those of voting and holding office.

SEC. 55. The terms of office of the Section Chairman and Secretary shall coincide with that of the President of the INSTITUTE. They may or may not be eligible for reëlection as prescribed in the Section by-laws.

SEC. 56. The Board of Directors may at any time rescind the authorization of any Section and terminate its existence.

SEC. 57. Papers and discussions presented before a Section or Branch shall be the property of the INSTITUTE, and may be published only on authorization of the Editing Committee.

SEC. 58. The Executive or other suitable Section or Branch committee in charge shall be responsible to the Editing Committee for all Section or Branch papers and discussions. Such matter as is approved by such local Section or Branch committee, as suitable for publication in the PROCEEDINGS, shall be presented to the Secretary of the INSTITUTE for consideration by the Editing Committee, who in judging its suitability shall be governed by the same reasons as are applied to similar matter offered for presentation at INSTITUTE meetings.

SEC. 59. Section or Branch papers and discussions not published in the PROCEEDINGS may be published elsewhere, with the statement that they have been presented before such Section or Branch, provided that previous approval of such publication has been secured from the Section or Branch committee in charge, and from the Editing Committee. The Editing and the Section or Branch committees may authorize the publishing of a Section or Branch paper or discussion without reference being made to its presentation before the Section or Branch.

SEC. 60. It shall be the duty of the Secretary of the Section to send to the Chairman of the Sections Committee, on or before October 1st of each year, an estimate of the appropriation required from the INSTITUTE for the expenses of the Section during the year ending the 30th of the following September. The Sections Committee shall apportion among the Sections such appropriation as may be authorized by the Board of Directors, and shall notify the Secretary of each Section of the amount apportioned to it. Such amounts may be drawn upon only for the reasonable expenses of the engineering meetings of the Section upon presentation of original bills endorsed by the Section Secretary and for the transportation expenditures of the Section's official delegate to the Annual Convention.

### STUDENTS.

SEC. 61. Any person pursuing a regular course of undergraduate study in electrical subjects, in any university or technical school of recognized standing, may be enrolled as a "Student of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS," as hereinafter provided.

SEC. 62. Each application for enrolment as a Student shall be endorsed by a member of the INSTITUTE. It shall be passed upon by the Board of Examiners, and submitted to the Board of Directors for action.

SEC. 63. The annual Student fee shall be three dollars ($3.00), payable in advance. The period of Student enrolment shall not exceed three years, and shall date from the first of January nearest the date of filing application.

SEC. 64. The annual fee of three dollars ($3.00) paid by each Student shall be applied as a subscription to the PROCEEDINGS for the year covered by such payment.

SEC. 65. Students enrolled under the provisions of these By-laws shall each be entitled to receive the regular monthly PROCEEDINGS and ordinary notices of meetings. They will be permitted to purchase the current TRANSACTIONS at $3.50 per year during the period of their enrolment.

SEC. 66. Student privileges may be withdrawn at any time by the Board of Directors.

SEC. 67. A Student changing his mailing address without notifying the Secretary shall be entitled to available duplicate copies of parts of the PROCEEDINGS upon payment of twenty-five cents for each part.

### UNIVERSITY BRANCHES.

SEC. 68. Any member who may be connected with a university or technical school of recognized standing, having a course in electrical engineering, may, upon the approval of the Board of Directors, organize Student meetings, to be held under his direction, such Student meetings to be designated as (name of institution) Branch of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

SEC. 69. University Branches shall organize by appointment or election of an Executive Committee of any suitable number of which the said member shall be a member, and of which other members or the enrolled Students of the INSTITUTE may constitute the other members. This organization shall be subject to the approval of the Board of Directors. Other students in the electrical engineering course of the institution may attend the meetings, under conditions to be prescribed by the University Branch.

Sec. 70. The member, by whom the University Branch shall be organized, or the member who succeeds him on its Executive Committee, shall be responsible to the Secretary of the Institute, for the conduct of its affairs, and shall make regular reports to the Secretary, of the proceedings at its meetings.

Sec. 71. At the meetings held by University Branches the papers read and discussed may be either original papers, or may be papers read before one of the regular meetings of the Institute. The Secretary of the Institute may send to University Branches a limited number of advance copies of the papers of the Institute.

Sec. 72. The Institute shall publish, from time to time, a list of universities and technical schools in which University Branches have been organized, and brief notices of the proceedings of their meetings.

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# AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

## REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1908.

The Board of Directors presents herewith for the information of the Institute a report of its work during the year, of the various standing and special committees, and the financial standing of the organization.

The Annual Convention was held at Niagara Falls, June 25-28, 1907. The total registered attendance was 459. Thirty-two professional papers, including the President's annual address, the report of the Committee on a Code of Ethics, and the revised Standardization Rules, were presented and discussed.

The Board of Directors has held 11 regular monthly meetings and one special meeting during the year, and the Executive Committee one meeting.

Upon recommendation of the Finance Committee, and with the approval of the General Counsel, *advance* payments were made upon the Institute's share of the land occupied by the Engineers' building. The total amount paid was $81,000, covering nine out of the twenty annual instalments, up to and including July 1, 1916. These payments were made from the Land, Building and Endowment Fund.

Upon recommendation of the Finance Committee the Institute has purchased for investment $12,000.00, face value, New York City registered bonds drawing interest at 4½ per cent., which were paid for out of the current bank balance.

*Board of Examiners.*—Eleven meetings were held during the year, at which applications for election as Associates, enrolment as Students, and transfer to the grade of Member, have been reported to the Board of Directors as follows:

| | |
|---|---|
| Recommended for election as Associates | 1,588 |
| Not recommended for election as Associates | 8 |
| Recommended for enrolment as Students | 687 |
| Recommended for transfer to the grade of Member | 53 |
| Not recommended for transfer to the grade of Member | 23 |
| Held for further information | 8 |
| Total number of applications considered | 2,367 |

*Sections Committee.*—Prior to the adoption of the new Constitution a year ago the local organizations were divided into three classes: namely, Branches, University Branches, and Student Meetings. The total number of local organizations of all classes on April 30, 1907, was 33. Under the new Constitution the local organizations were divided into two classes: Sections and Branches. There are now 48 local organizations, 22 of which are Sections, and 26 Branches; an increase of 15 during the year. Of this number four are Sections, organized at Toledo, Cleveland, Norfolk, and the City of Mexico. The other 11 are Branches located in various parts of the country. In addition to the Sections and Branches organized during the year, the committee has received many inquiries from different cities respecting the organization of Sections. The reports of local secretaries show that 284 meetings were held at the different Sections and Branches during the year, with a total attendance of 11,604. At these meetings 204 original papers were presented, in addition to which 104 Institute papers were discussed. The increasing interest taken in section work as shown by the facts presented in this report is further indicated by the large number of visiting speakers who have at various times during the year been invited to take part in section and branch meetings. The results of the year's work are very encouraging, and there is every reason to believe there would be even a more satisfactory showing had all the local meetings been reported to the secretary of the Institute.

*Building Fund Committee.*—Notwithstanding the financial depression of the latter half of the year, the Building Fund Committee is able to report that the number of subscribers to the Fund has increased from 934 to 1,538. The amount subscribed during the year was $6,464.68, showing an average for the new subscribers of a little over $10.00 per capita. The amount collected and placed in the treasury of the Institute during the year by the committee was $10,780.23. The total amount now pledged by the efforts of the committee is $170,199.15, out of which $135,609.50 has already been collected. It will thus be seen that the Fund has made substantial and encouraging progress, and it is hoped that with the return of prosperity the remaining $15,000 required may be obtainable from the membership, so that the Institute may enter upon its second quarter of a century in 1909 absolutely free of debt. While the number of subscribers is already so large, it is believed that amongst those who have not yet subscribed, and especially amongst the newer members, there will be found enough public spirited men to extinguish the small amount of indebtedness not now provided for. The committee feels strongly the desirability of basing the subscription list as broadly as possible, and while it has been successful in securing some very large individual gifts, it has directed and is still directing its efforts more particularly in the line of smaller amounts.

*Standards Committee.*—The Standards Committe has held three meetings since its appointment. Through its members it has engaged in a number of conferences with representatives from other national associations, including the National Bureau of Standards, with a view to assisting in a movement for an international agreement as to standard of light. The work of recomputing a wire table is held in abeyance until the National Bureau of Standards announces the value of the temperature coefficient of resistivity of copper, which is being determined.

*Library Committee.*—The complete report of this Committee will be printed in the Institute PROCEEDINGS in the near future.

*Committee on Bibliography.*—The catalogue of the Latimer Clark

Library, which was presented to the Institute in 1901 by Dr. Schuyler Skaats Wheeler, is now ready for printing. A very large amount of painstaking effort has been expended upon this work, and the proofs have been carefully revised by many authorities both in this country and abroad.

*Meetings and Papers Committee.*—During the year this committee has arranged for eight regular and two special meetings and a meeting in honor of Lord Kelvin. The special meetings were on the subject of Forest Preservation and Technical Education, the latter under the auspices of the Educational Sub-Committee. A total of seventeen papers were read at these meetings.

The regular annual convention was held at Niagara Falls under the auspices of the last committee. Preparations are now being made for the coming convention at Atlantic City. About thirty-three papers, of which many are short, will be presented.

The committee has made a vigorous effort to publish the papers in the issue of the PROCEEDINGS immediately in advance of the meeting, and this result has been accomplished in all instances with one possible exception. It is believed that it is a great advantage for the membership at large to have the papers in their hands some days in advance of the meeting. The manuscripts for the convention papers have nearly all been received and will be published in the May and June PROCEEDINGS as far as possible.

It has been the practice of the committee during the present year to consider the various sub-committees as practically independent bodies, except so far as the arrangement of dates and the editorial revision of papers is concerned. The initiative in the choice of subjects, the soliciting and accepting of papers, etc., have been in the hands of sub-committees. This is believed to be the only practical method of conducting the work. The present arrangement of the sub-committees, if treated in a liberal spirit, seems to be a very desirable one.

Papers presented at the Section meetings have been considered by the same standard as the papers submitted for the New York meetings, and a number have been printed in the PROCEEDINGS during the year.

*Educational Sub-Committee.*—During the winter several meetings of this committee have been held in New York City. As a sub-committee of the Meetings and Papers Committee, the first function of this committee is to obtain papers on the subject of technical education, and to arrange for meetings. Accordingly a special meeting of the Institute was held on January 24, 1908, at which two papers on engineering education were presented. Eighteen members of the Institute took part in the discussion which followed.

The University Branches throughout the country were urged to take up the subject of technical education and devote a session to it, which many of them did. The chairman of this committee conducted the meeting on this subject at the University of Illinois. He also visited several other technical institutions during the year. The committee has arranged for the presentation of several papers on technical education at the coming convention at Atlantic City.

*Railway Sub-Committee.*—The Railway Committee during the past year has acted in conjunction with the Meetings and Papers Committee in obtaining papers and speakers on railway subjects. The committee suggests that one of its members be appointed on the Standards Committee, and that all matters relating to the standardization of railway apparatus or railway practices be referred to it by the Standards Committee. The field of usefulness of the Railway Committee appears to be threefold—acting in an advisory capacity to the Meetings and Papers Committee, the Standards Committee, and the High-Tension Transmission Committee, and while its activities have been largely limited to acting in conjunction with the Meetings and Papers Committee during the past year, it is probable that the continued existence of the committee will demonstrate the benefit resulting from broadening its duties.

*Editing Committee.*—Since September, 1907, there have been edited and published eight numbers of the PROCEEDINGS. The total number of pages of these PROCEEDINGS is 1494; of this total, 454 pages have appeared as Section I, 1040 pages as Section II. Of the 1040 pages in Section II, 580 pages were devoted to technical papers, and 460 pages to discussions. In editing the discussions, the Committee has endeavored consistently to make them approach the well established Institute standards of style as to substance and form.

This committee has conferred with the Meetings and Papers Committee in regard to the publication of Volume XXVI of the TRANSACTIONS. This conference has decided that the TRANSACTIONS for 1907, consisting of approximately 1850 pages of papers, discussions and reports, be printed in two parts. Part I is now at the bindery and Part II is in press. Both parts will probably be ready for distribution in July.

*Law Committee.*—The Law Committee held six meetings during the year. Its most important work has been the revision of the By-laws to conform to the new Constitution. In this work the committee was assisted by members of other committees and by suggestions and comments from Institute members. The proposed new By-laws are now in form for presentation to the Board of Directors.

Other matters to receive the attention of the committee during the year were: the discrepancy between the dates of the Annual Meeting as set forth in the Charter and in the Constitution; the resolutions of the past-presidents embodying several important suggestions; resolutions of the Toronto Section respecting an intermediate grade of membership in the Institute.

*Code Committee.*—The Code Committee has held five meetings during the year for the discussion of some of the more important changes which have been proposed for embodiment in the National Electrical Code. The committee requests that any member of the Institute who may have noted instances of ambiguity in the present rules of the code, bring the matter to the attention of Mr. C. M. Goddard, Secretary of the Underwriters Electrical Committee, 55 Kilby Street, Boston, Mass., preferably with a suggested modified wording to avoid the ambiguity.

The Code Committee was officially represented by its chairman at the meeting of the Underwriters National Electric Association, March 25 and 26; also of the meeting of the National Conference on Standard Electrical Rules on March 27, *Committee on Forest Preservation.*—This committee has devoted its efforts largely to emphasizing the importance of forest preservation from the standpoint of the protection of water powers. As a result of the suggestions of the committee, meetings devoted to this subject were arranged by the local officers of the Atlanta, Boston, Minneapolis, Pittsfield, and Urbana Sections. Through the coöperation of the Meetings and Papers Committee Mr. Gifford Pinchot read a paper on the "Conservation of Natural Resources" at a special New York meeting of the Institute.

Through the courtesy of the Forest Service copies of the report of the Secretary of Agriculture on Southern Appalachian and White Mountain Watersheds were sent to all members of the Institute.

In accordance with its instructions the committee transmitted to the members of congress the resolutions on forest preservation adopted by the Board of Directors, and the Institute was represented at the congressional hearing on the Appalachian Forest Bill by Messrs. Schoen and Waddell, who have already presented their report. That many members of congress do not appreciate the importance of the protection of water powers has been conclusively demonstrated during the present session, and this committee feels that the Institute as an organization as well as the individual members should exert all legitimate influence to further legislation tending to protect the head-waters of streams on which important water powers are located. It is only by the active efforts of every one interested that any results can be accomplished.

*International Electrotechnical Commission.*—No meeting either of the International Electrotechnical Commission or of the United States subcommittee has been held during the year. A meeting of the International Electrotechnical Commission is contemplated for next fall, in London.

Various communications have been received from the acting secretary of the International Commission, and replies have been forwarded. In particular, a glossary of terms, A-G, prepared by the British special committee on nomenclature, was received in February, for consideration. It was transmitted to the Standards Committee, and received the consideration of that committee in March. The opinion and suggestions of the Standards Committee were communicated to the acting secretary of the Commission in London, under date of March 19, 1908.

*Code of Ethics Committee.*—A reprint of the proposed Code was mailed to all members in September, 1907, with a request for suggestions and criticisms, and a large number of very interesting and valuable replies were received.

Two meetings of the committee have been held at which the subject was discussed, but definite action was not taken, as all the members were not present.

Upon invitation of the Faculty of Science of Columbia University, the chairman made an address upon the subject before the graduating class.

*Edison Medal Committee.*—Competition for the Edison Medal under the terms of the original "Deed of Gift Creating the Edison Medal" having been demonstrated a practical failure, a new and substitute deed of gift has been executed.

By the terms of the new deed, the Edison Medal is no longer open to competition, but is to be awarded for "Meritorious Achievement in Electrical Science, or Electrical Engineering, or the Electrical Arts."

The next important work before the committee is to formulate new By-laws to govern its proceedings in consonance with the new deed.

*Increase of Membership Committee.*—This committee has been continuously active in bringing the advantages of Institute membership to the attention of desirable candidates. The number of applications for admission to the Institute as Associates received from October 1, 1907, at which time the present committee began its work, to April 30, 1908, is 874. No doubt a considerable number in addition will be received during the next few months, as a result of letters and printed matter already forwarded to prospective applicants whose names have been suggested to the committee.

*Membership.*—The present total membership and the increase during the past year are indicated below:

| | Hon. Mem. | Mem. | Asso. | Total |
|---|---|---|---|---|
| Membership April 30, 1907 | 2 | 536 | 3,983 | 4,521 |
| Additions: | | | | |
| New associates | ... | ... | 1,361 | .... |
| Transferred | ... | 43 | .... | .... |
| Deductions: | | | | |
| Died | 1 | 1 | 21 | .... |
| Resigned | ... | 3 | 54 | .... |
| Dropped | ... | 2 | 126 | .... |
| Transferred | ... | ... | 43 | .... |
| Membership April 30, 1908 | 1 | 573 | 5,100 | 5,674 |

Net increase in membership during the year........................1,153

*Resignations.*—The following Members and Associates have resigned during the year in good standing:

Members.—C. Batchelor, D. H. Fitch, George A. Redman.

Associates.—P. L. Anderson, C. A. Babtiste, C. D. Bailey, T. P. Bailey, F. P. Beach, T. W. Blake, J. H. Brown, J. S. Butler, P. G. Chace, E. H. Clarke, F. E. d'Humy, R. N. Dickinson, T. E. Doubt, G. F. Durant, J. M. Eglin, A. S. Fairbanks, T. Z. Franklin, C. Furgueson, W. H. Gallaher, L. T. Girdler, Louis Glass, H. C. Goldrick, Heatley Green, E. C. Hall, L. I. Hall, N. H. Heft, C. M. Heminway, Ho Hidetaro, J. S. Hill, Robert Hiltbrand, E. Hockett, A. C. King, A. H. Lidderdale, A. Marston, H. H. B. Meyer, S. A. Moss, L. C. F. Nautre, J. S. Neave, E. J. O'Beirne, A. G. Palgrave, C. C. Parks, H. A. Pharo, A. Pratt, L. W. Pratt, W. T. Ritchie, Bernard Rowntree, A. Hugh Scott, Oliver Shiras, J. F. Skirrow, B. K. Sweeney, H. P. Tewksbury, J. C. Walter, A. J. Wood, F. V. Young.

Total resignations, 57.

*Deaths.*—The following deaths have occurred during the year:

Honorary Members.—Lord Kelvin.

Members.—C. K. Stearns.

Associates.—F. C. Barr, U. S. Bell, T. V. Bolan, E. B. Brisley, E. Danielson, L. J. Deremo, C. D. Howell, W. A. Kreidler, L. J. Magee, C. P. Matthews, L. K. Perot, W. J. Phelps, H. L. Price, O. R. Roberson, Paul Robinson, J. M. Simpson, J. J. Skidmore, L. W. Snowden, F. P. Spiese, D B. Watson, Charles Williams, Jr.

Total deaths, 23.

*Delinquent.*—Dropped as delinquent during the year, 128.

The average receipts and disbursements *per capita* for the past seven years, are shown in the following table:

### RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

| Year | 1902 | 1903 | 1904 | 1905 | 1906 | 1907 | 1908 |
|---|---|---|---|---|---|---|---|
| Membership, April 30th, each year | 1549 | 2230 | 3027 | 3460 | 3870 | 4521 | 5674 |
| RECEIPTS PER MEMBER: | | | | | | | |
| Entrance Fees | $1.16 | $1.59 | $1.65 | $0.83 | $0.75 | $0.90 | $1.21 |
| Dues | 10.06 | 9.01 | 9.33 | 9.30 | 9.47 | 8.95 | 9.36 |
| Transactions, Sales, Advertising | 1.54 | 1.79 | 2.11 | 1.70 | 2.15 | 1.81 | 1.83 |
| Badges | .26 | .35 | .39 | .28 | .27 | .30 | .43 |
| Interest | .24 | .21 | .18 | .21 | .13 | .25 | .18 |
| | $13.26 | $12.95 | $13.66 | $12.32 | $12.77 | $12.21 | $13.01 |
| DISBURSEMENTS PER MEMBER: | | | | | | | |
| Transactions | $3.50 | $4.67 | $3.43 | $3.77 | $3.33 | $2.83 | $3.51 |
| Salaries | 2.78 | 2.49 | 2.50 | 2.20 | 2.64 | 2.53 | 2.55 |
| Meeting Expenses, incl. Sections | 1.13 | .87 | 1.16 | .82 | .68 | .68 | .91 |
| Housing | .94 | .65 | .79 | .75 | .68 | 1.33 | 1.15 |
| Library, incl. Salaries | 1.85 | 1.38 | 1.39 | .81 | .69 | 1.37 | .51 |
| Postage | .51 | .69 | .66 | .66 | .58 | .59 | .65 |
| Stationery and Miscel. Printing | .53 | .96 | 1.01 | .70 | .78 | .85 | .80 |
| General Expenses | .59 | .52 | .45 | .54 | .29 | .43 | .62 |
| Badges | .19 | .27 | .35 | .25 | .22 | .29 | .40 |
| Express | .15 | .15 | .28 | .22 | .23 | .28 | .14 |
| Advertising | | | | | .36 | .30 | .35 |
| Office Fittings | | | | | | .14 | .14 |
| Total | $12.17 | $12.65 | $12.02 | $10.72 | $10.48 | $11.62 | $11.73 |
| Credit Balance per Member | $1.09 | $0.30 | $1.64 | $1.60 | $2.29 | $0.59 | $1.28 |

### LAND, BUILDING AND ENDOWMENT FUND.

| RECEIPTS. | | DISBURSEMENTS. | |
|---|---|---|---|
| Before appointment of Committee | $ 6,100.00 | Paid United Engineering Society, acct. of contract | $ 8,000.00 |
| Collected by Committee | 135,609.50 | Paid United Engineering Society, acct. of mortgage | 99,000.00 |
| Interest on balances | 4,998.40 | Paid United Engineering Society, acct. of interest | 16,289.45 |
| | | Expenses of Committee | 6,146.10 |
| | | Paid for Furniture and Fittings, Engineers Building | 3,924.04 |
| | | Balance in bank, May 1, 1908 | 13,348.31 |
| Total | $146,707.90 | Total | $146,707.90 |

### GENERAL FINANCIAL STATEMENT.

New York, May 13, 1908.

MR. H. G. STOTT,
*President American Institute of Electrical Engineers,*
No. 33 West 39th Street, New York City.

*Dear Sir*: The Finance Committee has during the past year conformed to the provisions of the Constitution and By-laws describing the duties of the committee. It respectfully submits herewith the report of the chartered accountants, Messrs. Peirce, Gimson & Company, who have audited the books of the Institute for the year.

The committee has personally examined the securities held by the Institute, and found them to be as stated in the balance sheet.

In accordance with instructions from the Board, your committee has invested a part of the Institute's surplus funds in high grade securities and in view of the prosperous condition of the Institute, believes that additional security and increased income can be had by continuing to follow this policy of investing surplus funds not required for immediate use, in high-grade bonds.

Respectfully submitted,

CALVERT TOWNLEY,
Chairman Finance Committee.

---

New York, May 14, 1908.

MR. CALVERT TOWNLEY,
*Chairman Committee on Finance.*

*Sir*: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1908.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit A. Balance sheet, April 30, 1908.
Exhibit B. Receipts and disbursements for general purposes for year ended April 30, 1908.
Exhibit C. Receipts and donations for designated purposes, also expenditures on same for year ended April 30, 1908.
Exhibit D. Condensed cash statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,

PEIRCE, GIMSON & CO.,
Certified Public Accountants.

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New York, May 14, 1908.

MR. CALVERT TOWNLEY,
*Chairman Committee on Finance.*

*Dear Sir*: Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1908, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1908, and that the accompanying statements of Cash Receipts and Disbursements are correct.

PEIRCE, GIMSON & CO.,
Certified Public Accountants.

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

### BALANCE SHEET APRIL 30, 1908.

EXHIBIT A.

| ASSETS. | | |
|---|---|---|
| **CASH:** | | |
| Land, Building and Endowment fund | $13,348.31 | |
| Carnegie (Library) fund | 3,168.19 | |
| General Library fund | 244.15 | |
| Compounded Membership fund | 5,600.00 | |
| *Mailloux fund | 1,017.35 | |
| International Electrical Congress of St. Louis, 1904, Library fund | 2,253.34 | |
| | | $25,631.34 |
| †General cash in bank | 12,225.71 | |
| Secretary's petty cash on hand | 500.00 | |
| | | 12,725.71 |
| United States Government Bonds 3s, 1918 | 8,000.00 | |
| Premium on Bonds | 320.00 | |
| | | 8,320.00 |
| New York City 4½% Gold Bonds, 1957 | 12,000.00 | |
| Premium on Bonds | 677.50 | |
| | | 12,677.50 |
| Equity in Societies Building (25 to 33 West 39th Street) | 353,346.61 | |
| One-third cost of land (25 to 33 West 39th Street) | 180,000.00 | |
| | | 533,346.61 |
| Library volumes and fixtures | 25,375.88 | |
| Transactions | 4,654.75 | |
| Office furniture and fixtures | 5,215.04 | |
| Works of art, paintings, etc | 2,300.00 | |
| Badges | 576.35 | |
| | | 38,122.02 |
| **ACCOUNTS RECEIVABLE:** | | |
| Members for past dues | 11,365.75 | |
| Members for entrance fees | 425.00 | |
| | | 11,790.75 |
| Miscellaneous | 289.54 | |
| Subscriptions | 26.98 | |
| For advertising | 2,007.25 | |
| | | 2,323.77 |
| Total Assets | | $644,937.70 |

| LIABILITIES AND SURPLUS. | | |
|---|---|---|
| **FUNDS:** | | |
| Land, Building and Endowment Fund | $13,348.31 | |
| Carnegie (Library) Fund | 3,168.19 | |
| General Library Fund | 244.15 | |
| Compounded Membership Fund | 5,600.00 | |
| Mailloux Fund | 1,017.35 | |
| International Electrical Congress of St. Louis, 1904, Library Fund: | | |
| Principal | 2,146.12 | |
| Unexpended Income | 107.22 | |
| | | $25,631.34 |
| Reserve fund (U. S. Govt. Bonds) | | 8,320.00 |
| United Engineering Society (for cost of land) | | 81,000.00 |
| Total liabilities | | $114,951.34 |
| **SURPLUS:** | | |
| In cash | $12,243.06 | |
| New York City bonds | 12,677.50 | |
| In property and accounts receivable | 505,065.80 | |
| | | 529,986.36 |
| Total liabilities and surplus | | $644,937.70 |

* The Farmers' Loan and Trust Co. deposit account includes $17.35 of the Mailloux Fund.

† $75.00 of the Weaver donation.

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

### RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1908.

EXHIBIT B.

| RECEIPTS. | | |
|---|---|---|
| Entrance Fees | $6,865.00 | |
| Current Dues | 45,036.73 | |
| Past Dues | 4,088.75 | |
| Advance Dues | 182.50 | |
| Students' Dues | 3,323.00 | |
| Transfer Fees | 460.00 | |
| Badges | 2,442.00 | |
| | | $62,397.98 |
| Sales, Transactions, etc. | 1,240.77 | |
| Subscriptions, Proceedings | 1,085.90 | |
| Advertising | 7,782.87 | |
| Binding | 71.00 | |
| Exchange | 20.65 | |
| INTEREST: | | |
| U. S. Govt. Bonds. | 240.00 | |
| Bank Balances | 770.30 | |
| Royalty | 154.40 | |
| | | 11,365.89 |
| Total | | $73,763.87 |

| DISBURSEMENTS. | | |
|---|---|---|
| Stationery and Printing | $4,559.27 | |
| Postage | 3,713.93 | |
| General Expenses | 2,460.69 | |
| Meeting Expenses | 2,436.60 | |
| Section Meetings | 2,749.82 | |
| Badges | 2,247.39 | |
| Salaries | 12,086.00 | |
| Dedication | 1,064.71 | |
| Office Furniture | 783.12 | |
| | | $32,101.53 |
| PROCEEDINGS—TRANSACTIONS: | | |
| Printing | 13,324.23 | |
| Salary | 2,392.00 | |
| Engraving | 830.96 | |
| Volumes | 4,202.70 | |
| Electrotyping | 1,008.66 | |
| Binding | 512.60 | |
| Express | 793.89 | |
| Advertising Commissions | 1,959.02 | |
| | | 25,024.06 |
| LIBRARY: | | |
| Furniture | 290.80 | |
| Librarians salaries | 1,314.00 | |
| Books and binding | 425.49 | |
| Library insurance. | 60.90 | |
| Moving expenses | 643.83 | |
| Miscellaneous | 165.96 | |
| | | 2,900.98 |
| United Engineering Society Assessments | | 6,533.33 |
| Total | | $66,559.90 |
| Excess receipts over disbursements deposited in general fund | | 7,203.97 |
| | | $73,763.87 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

### RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES, ALSO EXPENDITURES FOR YEAR ENDED APRIL 30 1908.

EXHIBIT C.

| RECEIPTS. | |
|---|---|
| Land, Building and Endowment fund, Donations, Interest, etc. | $14,335.85 |
| Carnegie (Library) Fund, Interest | 107.43 |
| General Library Fund, Interest | 7.15 |
| Compounded Membership Fund | 794.79 |
| International Electrical Congress of St. Louis, 1904, Library Fund, on account of Principal | 48.56 |
| International Electrical Congress of St. Louis, 1904, Library Fund, on account of Interest | 64.68 |
| Mailloux Fund, Interest | 30.00 |
| Weaver Donation | 100.00 |
| Total | $15,488.46 |
| Excess of Expenditures over Receipts (as below) | 82,819.32 |
| | $98,307.78 |

| EXPENDITURES. | |
|---|---|
| Land, Building and Endowment Fund, on account of Mortgage | $90,000.00 |
| Land, Building and Endowment Fund, on account of Interest and Expense | 7,133.61 |
| Carnegie (Library) Fund | 468.84 |
| Compounded Membership Fund | 660.13 |
| Mailloux Fund | 20.20 |
| Weaver Donation | 25.00 |
| Total Expenditures | $98,307.78 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

### CONDENSED CASH STATEMENT.

EXHIBIT D.

| | | |
|---|---|---|
| Cash on deposit April 30th, 1907 | $126,149.90 | |
| Secretary's petty cash, April 30th, 1907 | 500.00 | |
| | $126,649.90 | |
| Receipts for general purposes, Exhibit "B" | 73,763.87 | |
| Receipts for designated purposes, Exhibit "C" | 15,488.46 | $215,902.23 |
| Disbursements for general purposes, Exhibit "B" | $66,559.90 | |
| Expenditures for designated purposes, Exhibit "C" | 98,307.78 | |
| Expended for New York City 4½% Bonds | 12,677.50 | $177,545.18 |
| Balance on hand, April 30th, 1908 | | $38,357.05 |
| On deposit for designated purposes, Exhibit "A" | $25,613.99 | |
| On deposit for general purposes, Exhibit "A" | 12,243.06 | |
| Secretary's petty cash, Exhibit "A" | 500.00 | $38,357.05 |

### PROPERTY ACQUIRED DURING THE YEAR.

| | |
|---|---|
| Office Furniture and Fixtures | $783.12 |
| Library Books and Binding | 855.34 |

---

All outstanding bills due prior to May 1, 1908, have been paid. Respectfully submitted for the Board of Directors.

RALPH W. POPE, *Secretary.*

New York, May 19, 1908.

## REPORT OF THE LIBRARY COMMITTEE.

We beg to submit herewith our report giving the more important features of the growth and operation of the library for the year ending April 30, 1908; with a statement of the present condition of the several library funds and of the expenditures for the year.

The gifts to the Library through its members and others have numbered nearly 300 volumes together with a very large number of pamphlets as yet unlisted and not included in the statistics presented herewith. The total valuation of the books and pamphlets is now placed at $23,406.55 an increase of $855.34 for the year. The complete list of donors with the number of volumes presented by each is as follows:

### DONORS

| | |
|---|---|
| ADAMS, EDWARD D | 11 |
| AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS | 16 |
| ANDREWS, W. S | 4 |
| AUDEL & CO., THEO | 1 |
| BOSTON TRANSIT COMMISSION | 1 |
| BOUCHER, W. J | 9 |
| BUREAU OF LABOR, CONNECTICUT | 1 |
| CAMP, W. M | 1 |
| CHEMICAL PUBLISHING COMPANY | 4 |
| CLAYTON & CRAIG | 1 |
| CROSSMAN, T. E | 1 |
| CUSHING, H. C., JR. | 1 |
| DEPARTMENT OF THE INTERIOR | 1 |
| DOREMUS, DR. CHAS. A | 1 |
| DRAKE & CO., FREDERICK | 4 |
| ELECTRICIAN PRINTING AND PUBLISHING COMPANY, LONDON | 6 |
| ENGINEERING NEWS PUBLISHING COMPANY | 1 |
| FLOY, HENRY | 1 |
| FOWLER, W. H | 1 |
| FRANKLIN, PROF. W. S. | 1 |
| GAUTHIER-VILLARS | 1 |
| GENERAL ELECTRIC CO | 1 |
| HAMMOND, R | 1 |
| HENLEY PUBLISHING COMPANY, N. W | 2 |
| HERING, CARL | 2 |
| HOBART & ELLIS | 1 |
| JENKS, W. J | 1 |

| | |
|---|---|
| KANSAS GAS, WATER, ELECTRIC LIGHT & STREET RAILWAY ASSO | 1 |
| LIBRARY OF CONGRESS | 1 |
| LINDSAY, C. E | 1 |
| LOCKWOOD, THOMAS D | 1 |
| MCGRAW PUBLISHING COMPANY | 39 |
| MACMILLAN COMPANY, THE | 7 |
| MAILLOUX, C. O | 11 |
| MARTIN, T. C | 1 |
| MORTON, DR. WM. J | 1 |
| MUNICIPAL OWNERSHIP PUBLISHING BUREAU | 4 |
| NATIONAL CIVIC FEDERATION | 3 |
| NEW YORK EDISON COMPANY | 2 |
| OHIO ELECTRIC LIGHT ASSOCIATION | 2 |
| POOLE, CECIL P | 2 |
| PUBLIC SERVICE COMMISSION FOR THE FIRST DISTRICT | 23 |
| RAILROAD GAZETTE | 2 |
| SCIENTIFIC PUBLISHING COMPANY | 2 |
| SCRIBNER'S SONS, CHARLES | 1 |
| SHELDON, DR. SAMUEL | 1 |
| SPON AND CHAMBERLAIN | 5 |
| U. S. NAVAL INTELLIGENCE OFFICE | 6 |
| UNIVERSITY OF ILLINOIS | 1 |
| VAIL, J. H | 6 |
| VAN NOSTRAND, D., & CO | 2 |
| WOLCOTT, TOWNSEND | 1 |
| WEAVER, W. D | 66 |
| WESTERN UNION TELEGRAPH COMPANY | 1 |
| WESTINGHOUSE ELECTRIC AND MANUFACTURING COMPANY | 3 |
| WHITTAKER & CO | 4 |
| WILEY & SONS, JOHN | 6 |
| WYNKOOP, H. S | 1 |

The general statistics of the Library and its valuation are shown in the following tabulation:

STATISTICS OF LIBRARY, MAY 1, 1908

| Source | Titles | Volumes | Pamphlets | Valuation |
|---|---|---|---|---|
| Report of May 1, 1907 | 7649 | 11186 | 565 | $22,551.21 |
| PURCHASES: | | | | |
| Mailloux Fund | 4 | 11 | | 20.20 |
| Institute Appropriation | 82 | 84 | | 210.14 |
| Weaver Fund | 3 | 47 | | 25.00 |
| Periodicals | 160 | 253 | | 506.00 |
| GIFTS: | | | | |
| Edward D. Adams | 3 | 11 | | 39.00 |
| From all other sources | 75 | 236 | | 55.00 |
| Totals including duplicates | 7976 | 11828 | 565 | $23,406.55 |
| Duplicates | 308 | 609 | | 824.74 |

In the following table are given the figures for the total valuation of the library property including $290.80 expended for new stacks during the past year:

### Total Valuation

| | |
|---|---|
| Books | $23,406.55 |
| Stacks | 1,761.05 |
| Furniture, Catalogues, Cases, etc. | 208.28 |
| | $25,375.88 |

The following tabulations give the state of the five funds from which the Library Committee is entitled to draw:

### Donations (General Library Fund)

| Dr. | | Cr. | |
|---|---|---|---|
| Balance May 1, 1907 | $237.00 | | |
| Interest May 1, 1908 | 7.15 | Unexpended | 244.15 |
| | $244.15 | | $244.15 |

### Carnegie Fund

| Dr. | | Cr. | |
|---|---|---|---|
| Balance May 1, 1907 | 3529.60 | Wheeler Bibliography | 468.84 |
| Interest May 1, 1908 | 107.43 | Unexpended | 3168.19 |
| | $3637.03 | | $3637.03 |

### Mailloux Endowment Fund ($1000)

(Proceeds for the maintenance of certain sets of periodical publications)

| Dr. | | Cr. | |
|---|---|---|---|
| Balance May 1, 1907 | $ 7.55 | Subscriptions | 20.20 |
| Interest May 1, 1908 | 30.00 | Unexpended | 17.35 |
| | $37.55 | | $37.55 |

### International Electrical Congress of St. Louis, 1904, Fund

(Principal)

| | |
|---|---|
| Principal May 1, 1907 | $2097.56 |
| Additions to Fund | 48.56 |
| | $2146.12 |

(Proceeds)

(Available for the purchase of International Electrical Literature)

| Dr. | | Cr. | |
|---|---|---|---|
| Interest accrued prior to May 1, 1907 | 42.54 | | |
| Interest to May 1, 1908 | 64.68 | | |
| | $107.22 | Unexpended | $107.22 |

### Weaver Fund

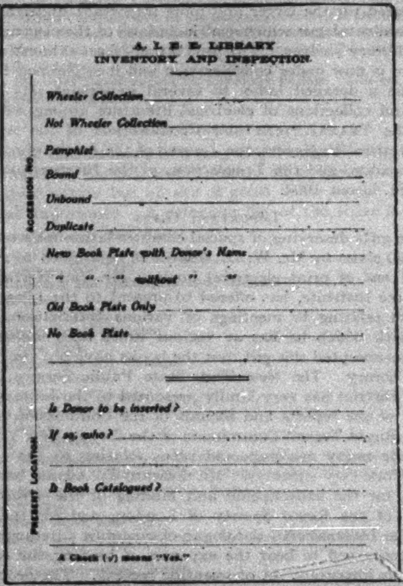
(For early and out of print electrical literature)

| Dr. | | Cr. | |
|---|---|---|---|
| Amount of Fund | $100.00 | Expended | $ 25.00 |
| | | Unexpended | 75.00 |
| | | | $100.00 |

### Institute Appropriation Account

| Dr. | | Cr. | |
|---|---|---|---|
| Appropriation for Maintenance for Year ending October 31, 1907 | $3500.00 | Insurance | $ 60.90 |
| | | Salary, Librarian<br>" Assistant | 1314.00 |
| | | Binding | 215.35 |
| | | Supplies | 41.62 |
| | | Subscriptions | 40.74 |
| | | Express and Postage | 6.90 |
| | | Books | 210.14 |
| | | Fixtures | 290.80 |
| | | Miscellaneous | 76.70 |
| | | Moving | 643.83 |
| | | Unexpended | 599.02 |
| | | | $3500.00 |

The above table shows total expenditures of $2900.98 out of the entire appropriation of $3500.00. The salary account is increased nearly $500 by reason of the additional attendance made necessary by keeping the Library open evenings until nine o'clock. The binding of many volumes of periodicals left over from previous years in an unbound form has increased this item of expense from $135.00 to $215.00. "Fixtures," which


A. I. E. E. LIBRARY
INVENTORY AND INSPECTION

ACCESSION NO.

*Wheeler Collection* ______
*Not Wheeler Collection* ______
*Pamphlet* ______
*Bound* ______
*Unbound* ______
*Duplicate* ______
*New Book Plate with Donor's Name* ______
*" " " without " "* ______
*Old Book Plate Only* ______
*No Book Plate* ______

PRESENT LOCATION

*Is Donor to be inserted?* ______
*If so, who?* ______
*Is Book Catalogued?* ______

A Check (✓) means "Yes."

cost $290 this year against $73 last year, include new book stacks and shelving. It should also be pointed out that the entire expense of moving the Library from Liberty Street to the new Engineers' Building, $643.83, is included in the disbursements for this year.

### GENERAL INVENTORY AND INSPECTION

It has been found necessary to make a complete inventory and inspection of the books and pamphlets on the shelves, preparatory to making a complete subject catalogue which will include all of the material possessed by the library. This work has progressed continuously for several months by a personal examination of each book and pamphlet, a permanent record being made on cards to show the exact condition of each item with relation to the library records. The card reproduced herewith shows the character of the information obtained by this inventory.

When this work is completed the library will not only be in excellent and most satisfactory and well arranged condition as regards many of the minor details that have not heretofore had proper care, but will also be well prepared for the larger and more important undertaking of producing the card catalogue which shall include all of the electrical literature now on the library shelves. The production of an exhaustive catalogue of this nature is now under consideration and it is planned to include in this catalogue a detailed index to several important sets of electrical periodicals and collections of electrical literature among which may be mentioned the TRANSACTIONS and PROCEEDINGS of the American Institute of Electrical Engineers, the *Journal* of the Institution of Electrical Engineers, London, and the *Transactions* of the International Electrical Congress of St. Louis, 1904.

### IMPORTANT GIFTS

Among the gifts deserving of special commendation may be mentioned a fund of $100 given by Mr. W. D. Weaver to be applied to the purchase of early and out of print electrical books. Mr. Carl Hering, a former president of the Institute, has offered to present to the Library a collection of books relating to meetings of various International Electrical Congresses with which he has at various times been associated. The committee has accepted this gift, but the books have not yet been turned over to the library. The New York State Public Service Commission for the First District has very kindly presented to the Library an almost complete set of the reports and records of the Commission and its predecessor, the Rapid Transit Commission of the City of New York. These records include many drawings and plans relating to the construction of the New York City subways. Mr. Edward D. Adams has again met the expenses for the subscription and binding of the *Proceedings* and *Transactions* of the Royal Society of London, and for the additional volumes of the International Catalogue of Scientific Literature. He has also kindly consented to bear the expenses of binding the entire set of volumes of this important set of scientific records. The proceeds of the fund presented by Mr. C. O. Mailloux have again been drawn upon to furnish the yearly continuation of four important periodical sets originally presented by Mr. Mailloux to the Library. Mr. W. S. Andrews has set a worthy example to other members of the Institute by presenting four items of very great historical interest including an original manuscript written by Mr. Thomas A. Edison in 1883, and an original note book compiled by Mr. Andrews from 1881 to 1885 while engaged in designing and installing Edison lighting plants. Mr. J. H. Vail has also presented several important books and pamphlets of historical interest chiefly relating to the early days of electric lighting in the United States.

### COMPLETION OF SETS

The Library has been very fortunate in being able to complete several important sets which heretofore it possessed in very incomplete form; among these may be mentioned:

American Street Railway Investments; Vols. 1 to 14.
Boston Transit Commission; Annual Reports, Vols. 1 to 13.
New York Public Service Commission for the First District; complete set of reports.
American Bell Telephone Company and American Telephone and Telegraph Company; a complete set of annual reports, 1881 to 1907.
Western Union Telegraph Company; a complete set of annual reports, 1874 to 1907.
General Electric Company; a complete set of annual reports, 1893 to 1908.
New York Edison Company and its predecessors; a complete set of annual reports.
New York State Railroad Commission's Reports; a complete set from 1883 to 1904.
American Street Railway Directory and its successors. This set has been made practically complete.
American Electrical Directory and its successors to date. This set has also been made practically complete.

### EARLY PERIODICALS

Mention should also be made of a long list of early electrical periodicals recently purchased at a small cost. Nearly all of these periodicals were transient in their nature but all are of great value to the Library from their historical importance. A complete list of the titles is here given:

Telegraphers' Advocate, New York.
Electrical and Street Railway Reporter
Electrical Doings, New York.
Electric Telegraph and Railway Review, London.
Boston Telegram.
Electrical Era, St. Louis.
Electrical Magazine, Washington.
The Wire, New York.
Popular Electric Monthly, Chicago.
Phonogram, New York.
Electrical Literature, Chicago.
Whipple's Electric Reports, Detroit.
Elektron, Boston.
Electricity, Cincinnati.
Electrical Industries Directory of Central Stations, etc., Chicago.
Directory of Electric, Cable and Horse Railways in the U.S. and Canada, New York.
Electrical Progress and Development, Boston.
Electrical Worker.
Street Railway News, New York.
Street Railway and Electrical News, St. Paul and Minneapolis.
Electrical News, Boston.
Electric Railway Advertiser, Boston.
Electricity and Railroading, Boston.
The Telephone, Chicago.
Electrical Northwest.
Electrical Items, New York.
Miscellaneous Bulletins of Electrical World, issued at the National Electric Light Association meetings.

A small collection of books has recently been purchased from the library of Mr. J. B. Stearns, one of the early inventors of telegraph apparatus. From this source a number of important items have been obtained not already in the library's collections.

### EXCHANGES

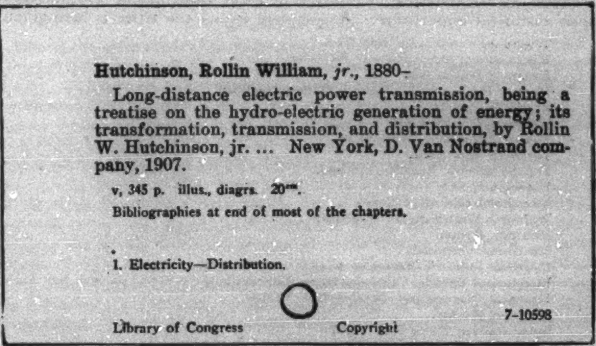
An effort has been made to increase the facilities of the Library by adding to the already large list of exchanges received from all parts of the world. Working in harmony with the other two Engineering Societies whose libraries are located with ours, a complete list of exchanges was made up numbering in all 561 titles. This long list of engineering periodicals has already been added to by the solicitation of other exchanges, and it is hoped at an early date to make the resources of the library in this particular far superior to those of any other engineering collection in the United States.

### RECENT BOOKS

An attempt has also been made during the past year to increase the facilities of our library by the addition of modern and recently published electrical books;and a large part of our purchases, aside from those made to complete deficiencies in existing sets have been along these lines.

### LIBRARY OF CONGRESS CARDS

In the cataloguing of recent books the use has been made of the Library of Congress printed cards. These are obtained from the Librarian of Congress at a nominal cost and when received are practically ready for use in the card catalogue. A sample of these cards is herewith given.



**Hutchinson, Rollin William,** ***jr.,*** **1880–**

**Long-distance electric power transmission, being a treatise on the hydro-electric generation of energy; its transformation, transmission, and distribution, by Rollin W. Hutchinson, jr. ... New York, D. Van Nostrand company, 1907.**

v, 345 p. illus., diagrs. 20$^{cm}$.

Bibliographies at end of most of the chapters.

1. Electricity—Distribution.

Library of Congress Copyright 7-10598

### OPENING OF THE LIBRARY ON WEEK DAY EVENINGS

Through the joint action of the American Institute of Mining Engineers, the American Society of Mechanical Engineers, and the American Institute of Electrical Engineers, the libraries of all three societies were opened to the public every evening until nine o'clock, except Sundays and legal holidays, beginning November 1, 1907. This has necessitated considerable additional expense for attendance, light, heat, elevator service, etc. The total attendance both day and evening for November, 1907 to April, 1908 is shown in the following table, (the attendance for November not being divided):

| | Day | Evening |
|---|---|---|
| November 1907 (total) | 570 | |
| December, 1907 | 275 | 371 |
| January, 1908 | 526 | 248 |
| February, 1908 | 439 | 241 |
| March, 1908 | 417 | 203 |
| April, 1908 | 403 | 210 |

### BIBLIOGRAPHY OF WHEELER COLLECTION

This work has been carried on this year under the direction of a special committee appointed by the Board of Directors so that no report by the Library Committee is called for.

### GIFTS DESIRED

The Library Committee solicits from members or others gifts of portraits, photographs, drawings and engineering sketches as well as books and pamphlets, many of which would be of great value to the resources of the library. Many of these can only be obtained through the cooperation of members.

Respectfully submitted,

The Library Committee

EDWARD CALDWELL,
*Chairman*
MORGAN BROOKS
MAX LOEWENTHAL
F. A. SCHEFFLER
PHILIP TORCHIO